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Smart Trench: Prototype of an Autonomous Water Defence System for 400kV Substation

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Abstract: *The presence of water inundating underground cables routed through electric utility buildings creates an ongoing risk to the continuity and reliability of the electric supply. Water build-up in underground cable trenches has led to degradation of cable insulation, corrosion of cable shields, and conditions that could cause false trips of electrical protection devices. This article describes a low-cost automated device for removing water from underground trenches called Smart Trench. Smart Trench utilises an ESP32 microcontroller as the central processing unit (CPU), combined with an HW 038 analogue water-level sensing device that detects the presence of water in the trench. Smart Trench has two submersible pumps, each activated and deactivated by optically isolated relays, and a five-state Finite State Machine (FSM) for full autonomous operation. The Smart Trench includes emergency manual override switches, as well as a weekly testing of the system whereby pumps are activated and deactivated concurrently to minimise pump seizure, along with a Web-based Internet of Things (IoT) Dashboard that can be accessed via a smartphone, and does not require separate applications to be installed. More than 350 flood and drain cycles were performed during testing, and results show that the Smart Trench activated the pumps 100% of the time on average. The average activation time for the pump was 3.4 seconds, and no electromagnetic interference (EMI) failure occurred. The Smart Trench had a total hardware cost of approximately INR 3,000. The Smart Trench is a commercially feasible and scalable solution that enhances safety in removing water from electric substations..*

Keywords: ESP32, substation automation, flood detection, HW 038, IoT web interface, EMI mitigation, finite state machine, drainage

I. INTRODUCTION

Maintaining the high-voltage substations used in the power transmission systems in India at full capacity and keeping them operating is essential to maintaining the reliable electricity supply for millions of Indian consumers, such as hospitals, factories, and residences. If one of these substations shuts down completely or even partially, there is the potential that millions of customers will have their electricity supply interrupted all at once.

A significant contributor to the reliability of these high-voltage substations is the condition of the underground cables that connect the substation to the transmission line. One of the most significant causes for cable failures in buried cable burial areas is water accumulating within the cable trench or cable hook. Any excess water found within either the cable trench or the cable hook could cause problems, such as taking years to dry out, eating into the insulation of the cables after extended periods of time, corroding any metallic components of the cables, and causing protective relays to trigger a fault in the grid that may not be present.

The trouble with inspecting the trench for water inside a substation is that technicians usually do not find out that there is water until after damage has been caused. At that point, any of the conductor cables that are in or near the trench may begin to fail (indicate failure). The relay signals that are sent to indicate whether there is water in the trench may become compromised. There is also a risk of causing a substation to lose power if a cable fault takes place due to water being present in the trench. Additionally, sending a technician to check the trench during the winter months is not a safe practice, because wet ground will heighten the risk of electrical shock when working around equipment that operates at high voltages. The IEEE 80 Standard describes the maximum allowable limits for touch and step voltages (the current paths through the body), which will generally be exceeded during the winter months due to the presence of water; therefore, both technician and access to service breaking the rule of IEEE 80 Standard 80 would result in a severe risk of injury.

This report outlines the Smart Trench, which is an autonomous controlled Pumping system developed with an ESP32 microcontroller (this is an embedded computer chip). The Smart Trench contains Stainless Steel sensors that can detect the level of water present and operate a pump to allow water to be pumped out of the trench without any human intervention. We designed and developed the Smart Trench so that it has the ability to be reliable in a substation yard that operates at 400 kV. The Smart Trench is designed with a 5 state controls, filtering to avoid false activation of the sensors, and has been designed around EMI to ensure reliability.

II. RELATED WORK AND PROBLEM FORMULATION

A. Traditional Drainage Methods

Battery-operated drain systems and gravity drain systems have historically been used to remove excess water from substation trenches. While gravity drain systems required frequent maintenance of the trench floors sloping toward sump pits, they were not intended to remove large volumes of water during rainy seasons. Additionally, battery-operated float switches are not typically very reliable because of debris buildup on the switches, causing them to fail, or they may have mechanical failures due to moving parts jamming up. Research has indicated that within two years, up to 12% of battery-operated float switches placed out in industrial environments may be inoperable at one time or another.

B. Microcontroller-Based Systems

Low-cost microcontrollers have opened up opportunities for companies to create better monitoring systems. One such microcontroller is called ESP32 and has been used in both environmental and water management applications because of its dual-core processing ability, Wi-Fi support, and low power draw. However, most of the current implementations of the ESP32 do not provide sufficient RF shielding; therefore, they are not suitable for use in high voltage substation yards.

C. Research Gap and Contribution

To address the missing parts for the Smart Trench, we have implemented:

- A solution without any moving parts (no float switches)
- EMI Protection in three different ways (Shielding, filtering and debouncing)
- A five-state, finite state machine which will increase reliability.
- An integrated IoT-based user dashboard with manual override capabilities.
- A modular and cost-effective solution (approx. INR 3000)

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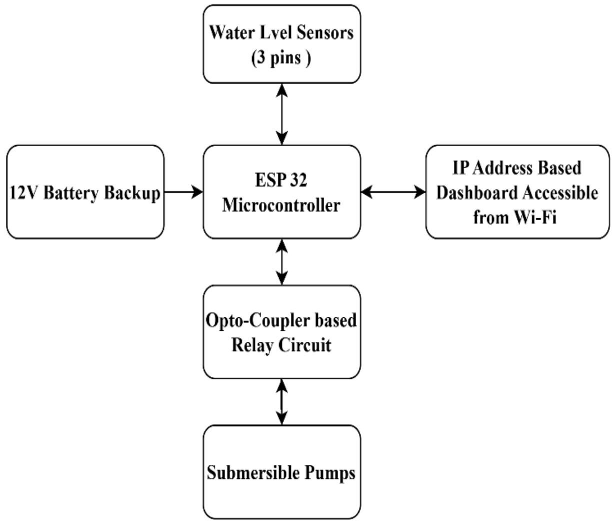

Fig. 1: Block diagram of the Smart Trench autonomous water evacuation system.

III. SYSTEM ARCHITECTURE AND HARDWARE DESIGN

A. Design Goals

When we selected the components for this product, we had set three design goals: (1) No Mechanical Moving Parts (Float Switches) do approximately 12% of their failure rate within two years when they installed outdoors in industrial environments; (2) Have adequate electrical isolation between the Control Electronic Low Voltage and Pump Circuits; (3) Provide Modularity for easy field replacement.

B. Control Unit: ESP32 Microcontroller

The brain of the system is the ESP32 from Espressif Systems. The ESP32 operates at 240 MHz and has two cores. Core 0 is used to read the water level sensors every 500 ms, while Core 1 manages all other background tasks (e.g., data logging, network communications) using the onboard hardware watchdog. The ESP32 can store enough firmware for the application and has a cost of approximately ₹350 each.

C. Water Level Sensing Probes

The HW 038 is an analogue (0-3.3 V) water level sensor that generates digital (0-4095) ADC values. The sensor will be mounted in a vertical position inside the trench with one end of the sensor touching the bottom of the trench. The calibration for this sensor will be determined for both when the trench is empty (the reading from the sensor) and when the trench is full (the reading from the sensor). Once the ESP32 receives the output from the sensor, it calculates a percentage of the amount of water in the trench based on the amount of analogue output from the sensor.

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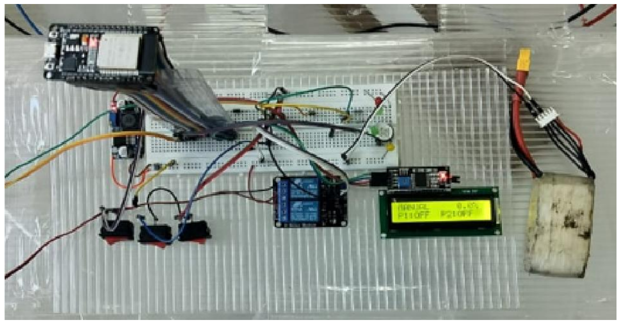

Fig. 2: Electronics assembly: ESP32, relay modules, and HW038 sensor.

D. Relay and Pump Control

Two 5V opto-isolated relay modules interface with the ESP32 and the two 12V DC submersible pumps. The optical isolation presents a physical light barrier between the ESP32 and the power circuits for the pump motors. Additionally, Flyback diodes are utilised across the terminals of each pump motor to absorb voltage transients (spikes) produced by the pumping motors when they are turned ON and OFF.

E. Power Supply and Backup

The entire system operates from a 12 V DC power supply that also provides 5 V and 3.3 V to operate the relays and ESP32, respectively. A 1000 µF capacitor on the 12 V rail absorbs the current surge created by starting the pump motor. A sealed 12 V/7 Ah lead-acid battery enables the entire system to continue operating for over 7 hours in the event of a failure of the mains power supply.

F. Emergency Override Switches

Two emergency push button switches (normally open) are wired to GPIO18 and GPIO5, using internal pull-up resistors. When the switch is pressed, it energises the associated pump regardless of the automatic cycling of each pump, thus providing a manual safety backup in case of an emergency.

IV. FIRMWARE ARCHITECTURE AND EMI MITIGATION

A. Five-State Finite State Machine (FSM)

The firmware is an architectural structure implementing a five-state finite state machine (FSM) to provide deterministic behaviour. The states/behaviours are detailed in Table I.

Table I - FSM States/Behaviours

State	Behaviour
IDLE	No water detected; pump turned off; sensors will be polled for readings every 500 milliseconds (0.5 seconds)
ALERT	Low probe detected as wet; waiting for 3 seconds to confirm wetness (debouncing)
PUMP	Flooding detected; relay turned ON; pump is actively draining the water
FAULT	The pump has run in excess of 8 minutes without clearing water; the pump has been turned OFF to protect the motor from damage
RECOVERY	Pump has been OFF for 5 minutes to cool down before transitioning back to IDLE

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B. False Trigger and Pump Cycling Prevention

Two mechanisms have been implemented to prevent rapid cycling of the pump:

Debounce filter:

Requires 10 consecutive "wet" readings (spaced 300ms apart for a total of 3 seconds) before transitioning from ALERT to PUMP. Eliminates false triggers caused by splashes and vibrations.

Hysteresis:

Once pumped, the low probe must remain dry for 15 continuous seconds, eliminating short cycling due to water surface suction effects.

C. Multi-Layer EMI Mitigation

Substations with 400kV operation should be protected against EMI with three layers of protection that are independent.

Physical shielding:

All probe signal cable is a twisted pairs inside grounded conduits. The ESP32 and its relay boards are housed in a grounded aluminium enclosure, giving them approximately 30 dB of shielding.

Signal filtering:

Each probe input pin has a 100 nF ceramic capacitor from each probe input pin to ground, forming a low-pass filter (cutoff 160 Hz with 10 k pullup resistor). The high-frequency pulses created by the relay will be attenuated by over 60 dB to remove EMI in the digital circuitry.

Software filtering:

The 10-sample debounce window is designed to ensure that any remaining transients cannot activate the pump. In the event of transients corrupting the program counter, the hardware watchdog timer (with a timeout of 30 seconds) will restart the system.

V. AUTONOMOUS CONTROL LOGIC

Every two seconds, the ESP32 processes data from the HW038 sensor, calculates the water level as a percentage based on the established empty and full points, and determines what action to take with the pumps based on four preprogrammed thresholds. The action is either stop both pumps (i.e., hysteresis) at the low threshold (20%), start the primary pump at the high threshold (70%), start the backup pump and activate an audible/visual alarm at the critical threshold (85%), or force both pumps on at the extreme threshold (95%), regardless of the operation mode.

A. Weekly Mock Drill

To avoid difficulties with pump seizure due to extended periods of inactivity, the system runs a one-time emergency mock drill every seven days. During this mock drill, pumps that are not already on are turned on for two seconds and then turned off. Each occurrence is logged as an event in the system event log.

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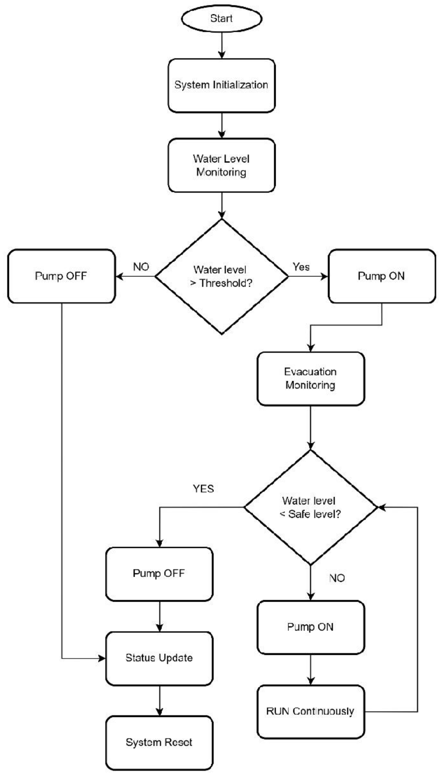
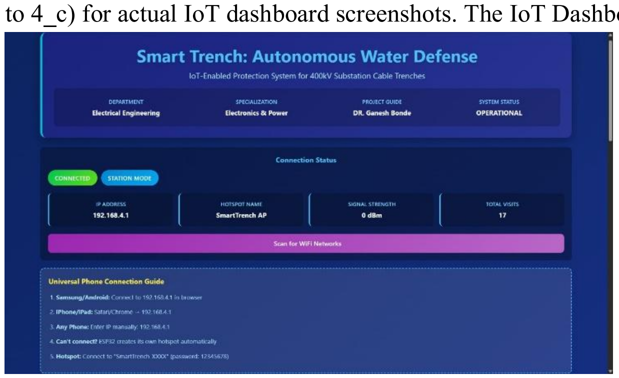


Fig. 3: Flowchart of the automatic water evacuation control logic.

VI. IOT DASHBOARD

The IoT Dashboard is a major component of the device, designed to give end-users the ability to monitor the functioning of their Sump Pump system in real time via an embedded web-based IoT dashboard hosted on the ESP32. The user can connect to the device's Wi-Fi access point(s) (e.g. the 'Smart Trench XXXX' access point when failed), using either a phone or a laptop, without the need for any external application or external server - thereby eliminating all potential installation issues. The Dashboard is comprised of three primary sections: connection status, control panel, and System Event Log.

Please reference Figures 4_a) to 4_c) for actual IoT dashboard screenshots. The IoT Dashboard will show:



Connection information

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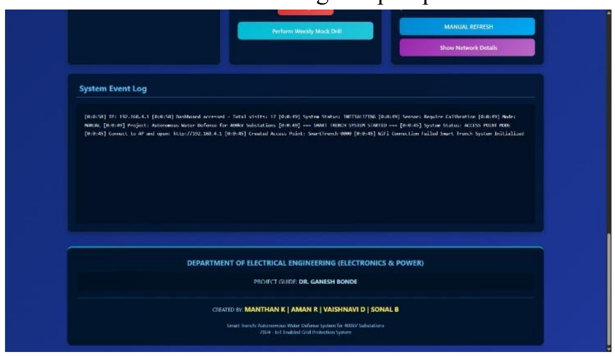
Water level monitoring and pump control.



System event log.

Fig. 4: Web-based IoT dashboard of the Smart Trench system.

- Current water level (% and raw ADC value)
- Pump status (ON/OFF) & Control Mode (AUTO/MANUAL)
- Alarm Indicator & Emergency Override Status
- Calibration Controls (EMPTY & FULL TRENCH Calibration)
- System Event Log with Time Stamps
- Manual Pump Controls (only in Manual Mode)
- Wi-Fi Scanner (to assist the operator in connecting to the network).

Users may switch from Automatic to Manual Mode, Start or Stop Pump(s) independently, and perform calibration of the HW-038 sensor from the browser.

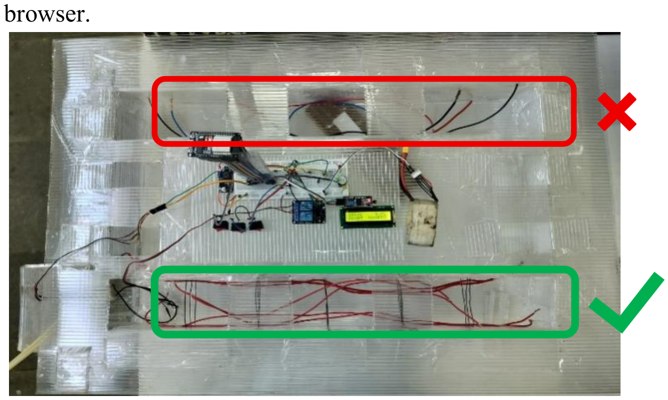


Fig. 5: Smart Trench prototype with Proposed Solution on Water Accumulation in Cable Trenches.

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VII. EXPERIMENTAL RESULTS

Test Setup

The testing setup involved an 80 cm × 20 cm × 20 cm clear acrylic aquarium filled with water with an HW-038 sensor at the bottom. The water was filled by an automated solenoid valve from a second microcontroller to perform the endurance performance test. After 50 automated flood & drain cycles, the tested system is ready for the endurance test.

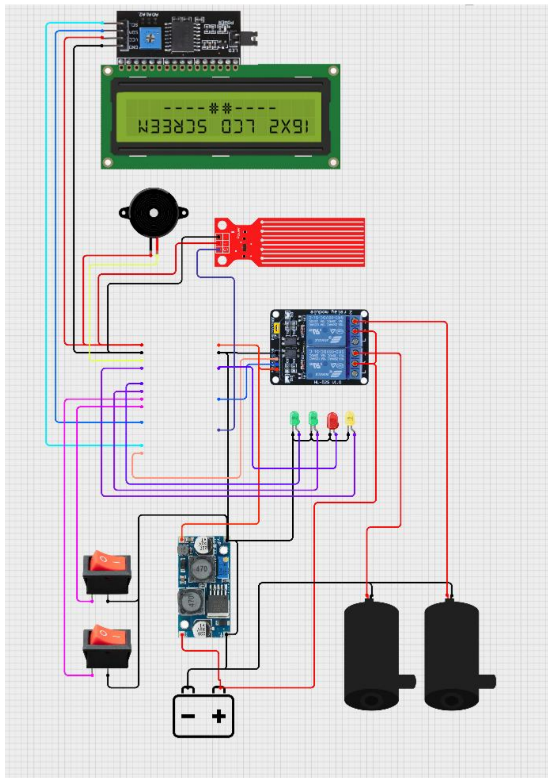

Fig. 6: Complete circuit diagram of the Smart Trench system.

Activation Speed and False Triggers

The test results are the outcomes from 50 test cycles, which had 0 false triggering, and every pump trigger was activated within 3.2 to 3.6 seconds after the 50 total test cycles.

Long-Run Reliability

The system performed flawlessly in testing over the entire 350 cycles; there were no missed activations or incorrect pump starts, and the watchdog timer was not triggered throughout the tests. At the conclusion of the testing, resistance measurements on the probes showed a change of less than 5%, which attests to the corrosion resistance of the stainless-steel probes. The evacuation rate of the pump remained consistent at 9.6 ± 0.5 L/min throughout the entire test period.

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TABLE III: Overall System Performance Summary

Parameter	Value
Activation Latency	3.3±0.14 s
Evacuation Rate	9.6±0.5 L/min
Quiescent Current	45±5 mA
Pump Operating Current	≈1 A
EMI-Induced Failures	0 events
Watchdog Timer Resets	0
Endurance Cycles Completed	50 cycles
Battery Backup Duration	> 7 hours
Total Hardware Cost	INR 3,000

Comparative Analysis

Table IV compares the Smart Trench with traditional methods.

TABLE IV: Comparison with Existing Drainage Methods

Feature	**Float Switch**	**PLC System**	**Smart Trench**
Moving parts	Yes	No	No
EMI protection	None	Moderate	High (3-layer)
Remote monitoring	No	Yes	Yes (IoT)
Cost (approx.)	INR 500	INR 15,000+	INR 3,000
Failure rate	12%	<1%	<1% (projected)

VIII. CONCLUSION AND FUTURE WORK

Smart Trench started as an answer to a simple problem, the presence of water in cable trenches is a significant issue in the area of 400kV substations, as it can cause large amounts of damage and the only current method of finding out whether there is water in cable trenches is to carry out routine manual inspections and use pumping to remove any water that does appear. We have created a low-cost, small-sized, embedded system capable of autonomously detecting the presence of water and providing an indication back to the ESP32 based on the logic that was programmed into it. The outcomes of testing have confirmed that the proposed solution is reliable, as it produced the correct response during all of the 50 test runs conducted, and it is also resistant to EMI. The 5 State firmware logic is easy to understand, and there are some features that provide additional levels of fault tolerance with respect to motor protection through the inclusion of an 8-minute fault timer and 5-minute recovery cool-down. The unit cost of INR 3,000 is a very strong financial justification when compared to the expense of a single cable fault, which could easily equal or exceed INR 2,000,000. Additionally, there is a very strong safety argument that proposes that removing people from the work required to maintain a hazardous area is, in itself, an excellent justification for the advancement of the Smart Trench, and its deployment in Indian substations can be accomplished with minimal changes to the current infrastructure.

Future work

We envision many upgrades that would be in line with our current prototype architecture:

- Usage of Cloud Monitoring to push data from various Trenches to one central monitoring point by the control room in Real Time
- Utilise the weather forecasts weather API to activate heightened monitoring in advance of heavy rainfall
- Install a small solar panel and charge controller to provide Energy Autonomy—free of grid power

- Include additional environmental logging sensors, such as Temperature, Humidity, and Water quality
- Coordinate (Integrate) Existing substation SCADA with the system using Modbus or DNP3 Protocols.

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