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KONTROLA NISKONAPONSKE MREŽE U REALNOM VREMENU

REAL-TIME MONITORING OF LV NETWORK

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KRATAK SADRŽAJ

Zelena energetska tranzicija menja način rada distributivnih elektroenergetskih sistema. Sve veća penetracija distribuiranih izvora energije, električnih vozila, toplotnih pumpi i aktivnih potrošača dovodi do povećane varijabilnosti tokova snage i češćih stresnih stanja u niskonaponskim (NN) mrežama. Mreže koje su prvobitno projektovane za pasivnu potrošnju sada moraju da funkcionišu u dinamičnim i delimično nepredvidivim uslovima. Iako su praćenje i upravljanje u realnom vremenu već dugi niz godina dobro uspostavljeni u srednjenaponskim mrežama, NN mreže i dalje ostaju u velikoj meri nevidljive, uz ograničenu dostupnost pravovremenih operativnih podataka. Tradicionalni pristupi zasnovani na periodičnim merenjima ili prijavama kvarova od strane korisnika više nisu dovoljni za podršku brzom donošenju odluka i efikasnom radu mreže u uslovima koji se stalno menjaju. Masovna primena pametnih brojila u okviru napredne merne infrastrukture pruža jedinstvenu priliku za unapređenje praćenja NN mreža. Savremena pametna brojila mogu da obezbede mnogo više od periodičnih očitavanja potrošnje energije; ona mogu da generišu događajno zasnovane alarme, da obezbede skoro realno-vremenske intervalne podatke i da podrže funkcije obrade i upravljanja na ivici sistema. Kada se pravilno integrišu u distributivne upravljačke sisteme, ove mogućnosti omogućavaju višeslojni pristup praćenju NN mreža u realnom vremenu. Ovaj rad predstavlja koncept praćenja NN mreža u realnom vremenu zasnovan na funkcionalnostima pametnih brojila. Prvi sloj se fokusira na praćenje zasnovano na alarmima, pri čemu pametna brojila generišu i prosleđuju alarme koji se odnose na prekide napajanja, gubitak faze i ponovno uspostavljanje napajanja ka centralnim sistemima u roku od nekoliko sekundi. Time se omogućava brzo otkrivanje neplaniranih događaja i unapređuje situaciona svest operatera mreže. Drugi sloj se odnosi na skoro realno-vremensko praćenje korišćenjem „push“ prenosa 15-minutnih i 1-minutnih intervalnih podataka ka IoT brokeru i višim analitičkim sistemima, čime se obezbeđuju detaljni uvidi u opterećenje mreže i ponašanje napona. Treći sloj razmatra primenu inteligencije na ivici sistema unutar pametnih brojila, gde lokalna obrada omogućava procenu napona i brze reakcije, uključujući generisanje alarma i upravljanje putem releja. Predloženi pristup je potvrđen kroz praktičnu primenu i testiranje u realnom okruženju distributivne mreže. U radu se opisuju osnovna arhitektura sistema, tokovi podataka i integracija sa postojećim operativnim sistemima, kao i operativni rezultati dobijeni kroz pilotne projekte i rane faze produkcione primene.

Ključne reči: pametna brojila, alarm, NN kontrolne funkcije, podatci u realnom vremenu

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ABSTRACT

The green energy transition is fundamentally changing the operation of distribution power systems. The increasing penetration of distributed energy resources, electric vehicles, heat pumps, and active consumers is leading to higher variability of power flows and more frequent stress conditions in low voltage (LV) networks. Networks that were originally designed for passive consumption are now required to operate under dynamic and partially unpredictable conditions. While real-time monitoring and control have been well established in medium voltage networks for many years, LV networks remain largely unobservable, with limited availability of timely operational data. Traditional approaches based on periodic measurements or customer-reported outages are no longer sufficient to support fast decision-making and effective network operation under evolving conditions. The widespread deployment of smart meters as part of advanced metering infrastructure provides a unique opportunity to enhance LV network monitoring. Modern smart meters are capable of delivering more than periodic energy readings; they can generate event-based alarms, provide near real-time interval data, and support edge-based processing and control functions. When properly integrated into distribution control systems, these capabilities enable a multi-layered approach to real-time monitoring of LV networks. This paper presents a comprehensive real-time monitoring concept for LV networks based on smart meter functionalities. The first layer focuses on alarm-based monitoring, where smart meters generate and push alarms related to outages, phase loss, and power restoration to central systems within seconds. This enables rapid detection of unplanned events and improves situational awareness for network operators. The second layer addresses near real-time monitoring using push transmission of 15-minute and 1-minute interval data to an IoT broker and higher-level analytical systems, providing detailed insights into network loading and voltage behavior. The third layer explores the use of edge intelligence within smart meters, where local processing enables voltage evaluation and fast response actions, including alarm generation and relay-based control. The proposed approach is validated through practical implementation and testing in a real distribution network environment. The paper describes the underlying system architecture, data flows, and integration with existing operational systems, as well as operational results obtained from pilot and early production deployments.

Keywords: Smart meter, alarm, LV control functions, real-time data

INTRODUCTION

To maintain secure and efficient operation, DSOs must significantly improve the observability of LV networks, as widely recognized in recent smart metering studies and CIRED working group publications [1], [2]. While real-time monitoring and control have been well established in medium voltage networks for many years, LV networks remain largely unobservable, with limited availability of timely operational data. Traditional approaches based on periodic measurements or customer-reported outages are no longer sufficient to support fast decision-making and effective network operation under evolving conditions.

Pilot use cases demonstrate local voltage evaluation using fixed time intervals and fast threshold-based control actions with response times below one second. Edge-based processing enables reduced latency and improved responsiveness while maintaining centralized visibility through alarm reporting.

The presented results confirm that smart meters can serve as a key enabler for real-time observability, advanced analytics, and future automation of LV network operation, providing a solid foundation for the digital transformation of distribution systems.

1 SYSTEM ARCHITECTURE AND DATA FLOWS

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1.1 Alarm-based real-time monitoring

Alarm-based monitoring represents the first and currently most mature layer of the proposed solution. Smart meters are configured to detect specific network events and automatically generate alarms using push communication. Typical alarm events include power-down ("last gasp"), power restoration, phase loss, and phase normalization.

When an event occurs in the LV network, the smart meter detects the condition within seconds and immediately transmits the alarm message to the HES via the mobile communication network. The HES processes the incoming alarms and forwards them in real time to downstream systems using a message-oriented architecture based on RabbitMQ (RMQ). This approach ensures reliable, low-latency delivery and decoupling between data producers and consumers.

In the current production environment, alarm-based monitoring is deployed on approximately 9,000 smart meters. The system operates continuously and generates a significant volume of alarms, which are further processed and visualized in the SCADA ADMS system. Alarm aggregation and correlation logic enable operators to distinguish between individual customer events and larger network incidents, such as feeder or transformer outages.

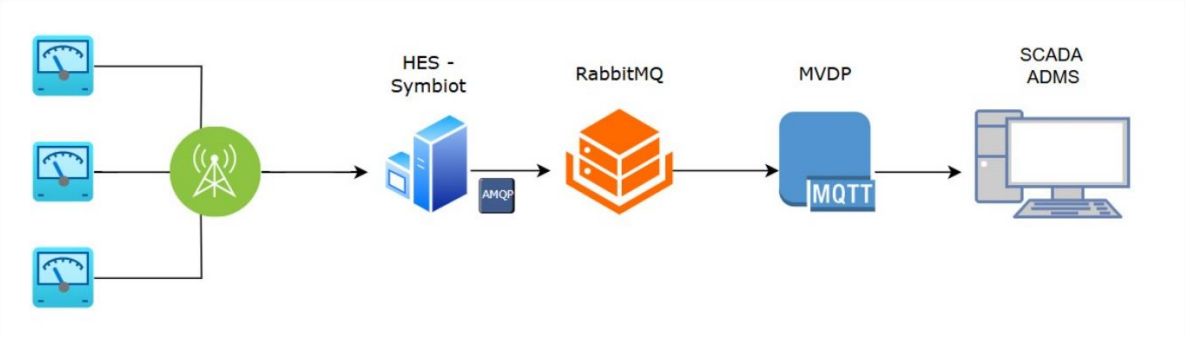


Figure 1: Alarm data flow from smart meters to SCADA

1.2 Near real-time interval data push to IoT broker

In addition to event-based alarms, smart meters are configured to push interval measurement data in near real time. This second data flow focuses on the transmission of 15-minute and 1-minute measurements, which provide deeper insights into LV network loading and voltage behavior.

Selected smart meters periodically transmit interval data to an IoT broker, from where the data is forwarded to higher-level analytical systems. Unlike traditional pull-based metering architectures, the push-based approach enables timely availability of measurement data for

monitoring and analysis purposes. Smart meter configuration defines which data points are transmitted, the reporting frequency, and the selection of meters participating in this data flow.

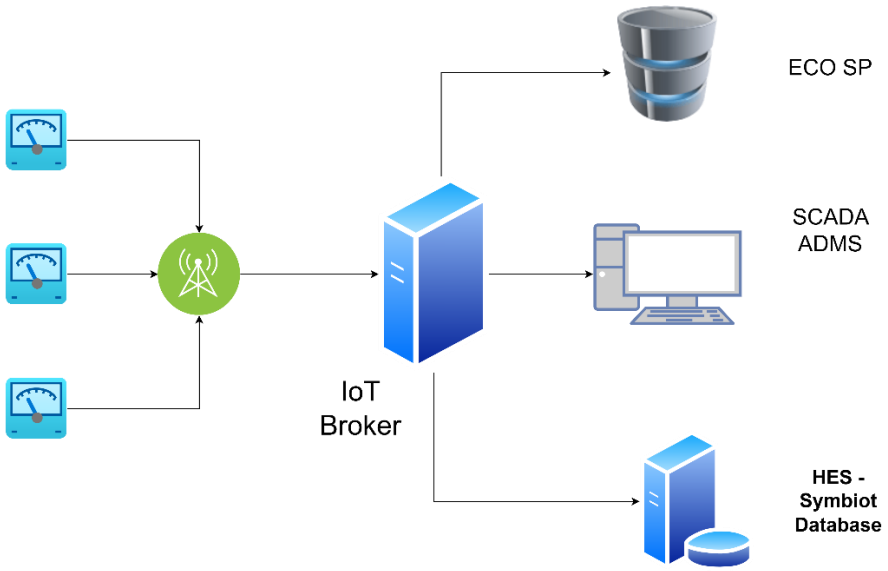


Figure 2: Push-based transmission of 15-minute and 1-minute interval data to IoT broker

The current implementation includes a subset of smart meters configured for near real-time data push. Statistical information about data volumes, reporting frequencies, and meter participation rates is collected and used to evaluate communication load and system performance. This data flow supports advanced analytics, including load profiling, voltage trend analysis, and identification of emerging network constraints.

1.3 Edge-based monitoring and control using smart meter EDGE module

The third layer of the proposed architecture introduces edge intelligence through the use of smart meter EDGE modules. In this approach, selected monitoring and control functions are executed locally at the smart meter, reducing latency and dependency on central systems.

In the first use case, voltage values are evaluated locally over fixed 10-minute time blocks (e.g., 00:00–00:10). If the calculated average voltage exceeds predefined thresholds (e.g., ±10% of the nominal voltage of 230 V), an alarm is generated and transmitted to the HES for further processing.

In the second use case, fast voltage threshold detection is implemented. When a predefined voltage limit (e.g., 240 V) is exceeded, the EDGE module activates a relay output within one second. The change in relay state is then reported as an alarm to the HES, providing both local response and centralized visibility.

At the time of writing, EDGE-based functionalities are in the pilot phase and are not yet deployed on a large scale. Nevertheless, the initial results demonstrate the potential of edge intelligence for fast reaction, improved voltage control, and future automation of LV network operation.

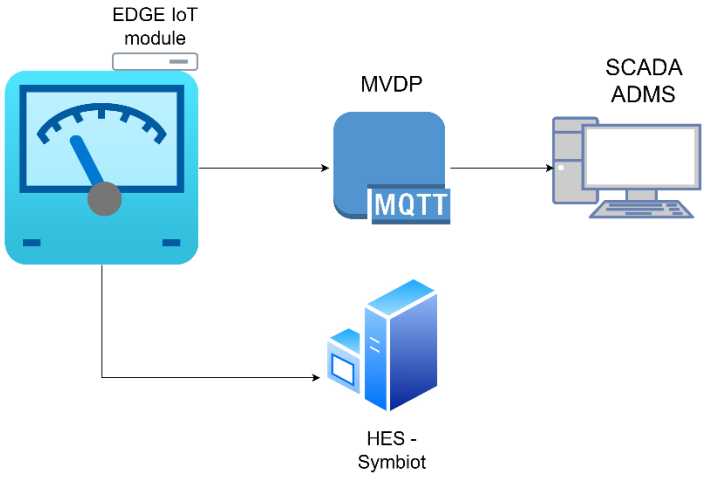


Figure 3: EDGE-based voltage monitoring and control use cases (Local processing, alarm generation, relay activation)

2 USE CASES AND OPERATIONAL RESULTS

Alarm-based monitoring using smart meters is currently deployed in a test environment and continuously supports real-time observability of the LV network, building upon concepts previously discussed for low voltage network operation [2]. For the purpose of evaluating operational performance, alarm data collected over a one-month period was analysed.

During the analysed period, a total of 63,497 alarm events were recorded from 7,606 smart meters configured for real-time alarming. On average, approximately 1,984 alarms per day were generated. The daily number of alarms varied significantly, ranging from 140 alarms on low-activity days to more than 23,800 alarms on days with pronounced network events, indicating a strong correlation between alarm volume and actual operating conditions in the LV network.

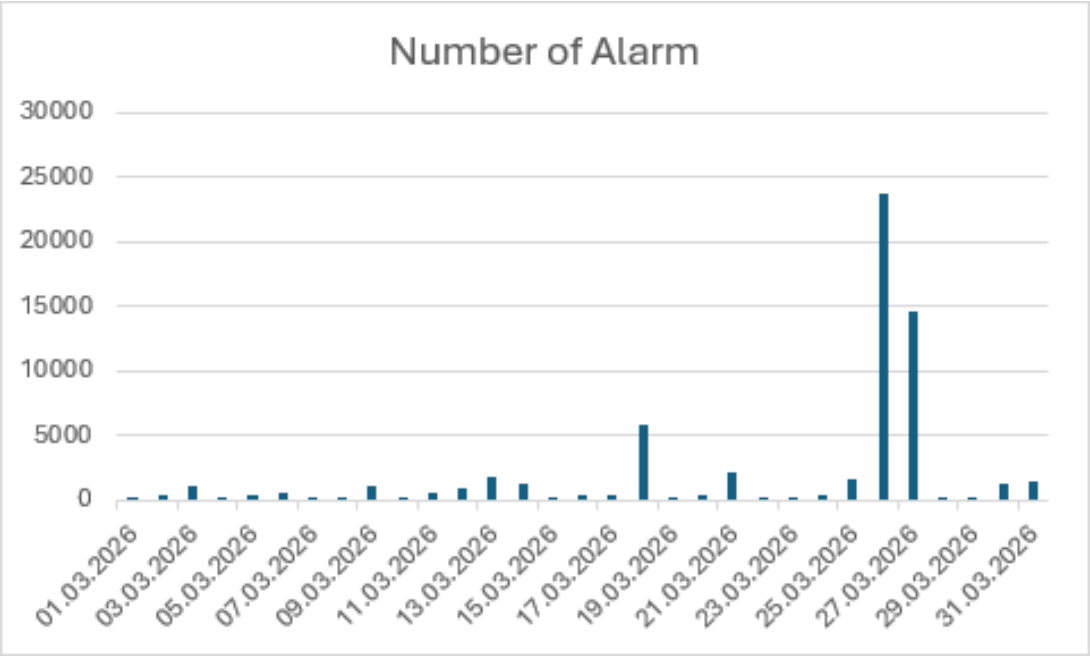


Figure 4: Number of alarm events over the analysed period

From an operational perspective, an important indicator is the proportion of smart meters generating alarms. On average, approximately 1.9% of all monitored smart meters reported at least one alarm on a given day.

On days with limited network disturbances, this share was typically below 0.2%, while during major events it increased to nearly 14.3%.

These results demonstrate that alarm generation is event-driven and does not impose unnecessary communication load during normal operating conditions.

The analysed data confirms that push-based alarm reporting provides timely and relevant information for LV network operation while maintaining efficient use of communication resources. The observed alarm volumes and meter participation rates indicate that the solution is well suited for further scaling. Based on current deployment trends, the number of smart meters supporting real-time alarming is expected to increase by approximately 10,000 devices **per year**, which further emphasizes the importance of scalable message handling and aggregation mechanisms.

2.1 Smart meter configuration and alarm lifecycle management

On smart meters configured for push-based alarming, alarm management is divided into two distinct mechanisms. The first mechanism is Push on Power Down, which is transmitted as a "last gasp" message. This message is sent to the HES database and subsequently forwarded to the SCADA ADMS system in the event of a complete loss of supply at the metering point.

In cases where only a single phase is lost or when power supply is restored to the smart meter, the Push on Alarm mechanism is used. In this case, the alarm is triggered by an event generated from Alarm Register 2 and immediately pushed to the HES.

Since alarm generation on the smart meter is based on descriptors that trigger the *Push on Alarm* mechanism and these descriptors are not automatically cleared by the meter itself, an automated process has been implemented within the HES. For each *Push on Alarm* received from a smart meter, a dedicated job is executed via the HES, which clears the corresponding descriptor and alarm register on the meter. This ensures that the smart meter is immediately ready to generate and transmit subsequent alarm events without manual intervention.

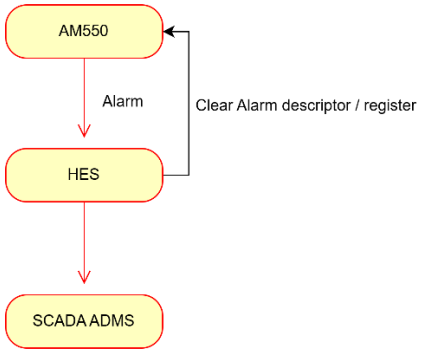


Figure 5: Alarm handling flow

As previously mentioned, with the continuous increase in the number of smart meters configured for push-based communication, it is necessary to closely monitor the performance of the HES system. Particular attention must be paid to message processing capacity and response times to ensure reliable and scalable alarm handling as the deployment grows.

2.2 Display of Meter Alarms in SCADA ADMS

A prerequisite for the correct display of alarms in the SCADA ADMS system is proper time synchronization. If the system clocks are not synchronized, events are displayed as invalid. This issue was resolved by implementing daily time synchronization.

Based on the agreement, a configuration change has temporarily been applied in ADMS by disabling the option “Creation of Incidents Based on Smart Meter Events” in all forecasting profiles.

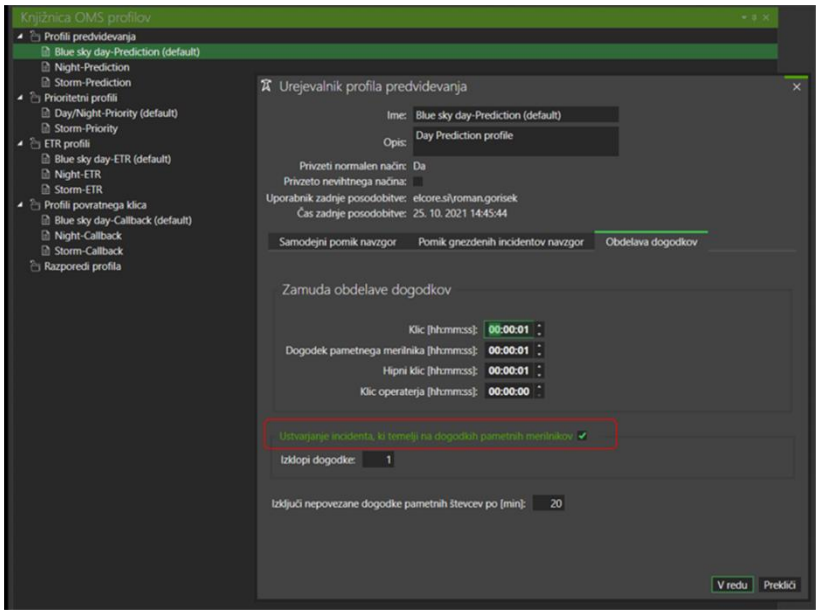


Figure 6: SCADA forecast profile settings

With this setting, the creation of incidents triggered by meter events has been disabled. However, smart meter events are still recorded in the meter event log and are processed in relation to incidents that are created based on SCADA data or manually within the network model.

3 CONCLUSIONS

Alarm-based monitoring using push communication has proven to be an effective and scalable solution for real-time detection of outages, phase loss, and restoration events in LV networks. Operational results from a production environment demonstrate that alarm generation is event-driven and communication-efficient, providing timely and relevant information without unnecessary system load. The integration of smart meter alarms into SCADA ADMS significantly improves situational awareness and supports faster fault localization and response.

Near real-time interval data push further enhances LV network observability by providing continuous insight into network loading and voltage behaviour. The transition from pull-based

to push-based data acquisition enables timely availability of measurement data but also results in a substantial increase in communication traffic.

The exploration of edge-based intelligence demonstrates additional potential for improving responsiveness and enabling new operational use cases. Local voltage evaluation and fast threshold-based control actions reduce latency and dependency on centralized systems, while still maintaining centralized visibility through alarm reporting.

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