КОМУНИКАЦИОНИ ПРИСТУП ЗА МОНИТОРИНГ КВАЛИТЕТА ЕЛЕКТРИЧНЕ ЕНЕРГИЈЕ У ПАМЕТНОЈ МРЕЖИ ЗАСНОВАН НА РАЧУНАРСТВУ У ОБЛАКУ

CLOUD-BASED COMMUNICATION APPROACH FOR MONITORING OF POWER QUALITY IN SMART GRID

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КРАТАК САДРЖАЈ

Нови комуникациони приступи се интензивно разматрају за примјене у паметној мрежи. Повећан број паметних бројила у нисконапонској мрежи и уређаја за мјерење фазора у високонапонској мрежи прогресивно трансформише традиционалну дистрибутивну мрежу ниске обсервабилности у модерну паметну мрежу са доступним разноврсним мјерним подацима. Комуникациони приступ заснован на рачунарству у облаку представља ефикасно, поуздано и повољно рјешење за остваривање погонских функција у паметној мрежи, чије извршавање није временски критично. Типичан примјер је мониторинг показатеља квалитета електричне енергије. Очекује се да анализа квалитета електричне енергије има значајан утицај на цијену електричне енергије и поузданост мреже у блиској будућности, те је она неизбјежна у будућој паметној мрежи. У овом раду је предложен комуникациони приступ за мониторинг квалитета електричне енергије у паметној мрежи заснован на рачунарству у облаку. „ThingSpeak” платформа отвореног софтвера за примјене интернета уређаја је искориштена за моделовање сервера рачунарства у облаку, док је модел паметне мреже реализован примјеном програмског пакета „MATLAB/Simulink”. Добро позната тестна мрежа „IEEE 13-bus” је искориштена за примјену функција мониторинга квалитета електричне енергије. Различити примјери су дефинисани у сврху испитивања карактеристика предложеног комуникационог приступа. Велики број симулација је извршен у циљу потврде ефикасности система за мониторинг квалитета електричне енергије. Посебна анализа је посвећена мониторингу напонског профила мреже са основним циљем детекције појава попут пропада напона, пренапона, хармонијске дисторзије, итд. Добијени резултати јасно указују на бројне предности и значајан потенцијал предложеног приступа.

Кључне речи: паметна мрежа, квалитет електричне енергије, интернет уређаја, комуникација и рачунарство у облаку, систем за мониторинг

ABSTRACT

The new communication approaches are intensively being considered for Smart Grid (SG) applications. Increased number of smart meters (SM) at low voltage levels and phasor measurement units (PMU) at high voltage levels progressively transform traditional distribution networks with low observability into modern SG with a variety of measurement data available. The Cloud-based communication approach represents an efficient, reliable, and low-cost solution for SG operating functions which are not time-critical. A typical example is the monitoring of power quality indicators. The analysis of power quality is expected to have a significant impact on electricity prices and system reliability in the near future and its consideration is inevitable for future SG. In this article, the Cloud-based communication approach is proposed for monitoring of power quality in SG. Internet of Things (IoT) open-source platform named ThingSpeak is used for modeling of Cloud server, while the SG model is created using MATLAB/Simulink software package. A well-known IEEE 13-bus test network is used as a basis for the implementation of a power quality monitoring function. Various case studies are defined to test the performance of the proposed communication approach. Extensive simulations are performed to validate the efficiency of the power quality monitoring system. A special analysis is dedicated to the monitoring of the network voltage profile with the main goal of detecting phenomena such as voltage drop, overvoltage, harmonic distortion, etc. The results obtained clearly indicate the numerous advantages and significant potential of the proposed approach.

Keywords: smart grid, power quality, internet of things, cloud-based communication, monitoring system

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1. INTRODUCTION

The most universally accepted standards for power quality are IEEE and IEC standards [1]. IEEE 519-1992 standard [2] defines established limits on harmonic currents and voltages at the point of common coupling (PCC) or point of metering [3]. Nowadays, the revised version of the IEEE 519 standard [4] is used for guidance in the design of power systems with nonlinear loads. Distribution and sub-transmission networks with nominal voltage ranges 120 V - 69 kV and 69 – 161 kV, respectively, are both subjects to analysis in the IEEE 519 standard. Standards IEC 61000-3-2 [5], IEC 61000-3-3 [6] and IEC 61000-3-4 [7] are relevant for electrical and electronic equipment intended to be connected to public low-voltage distribution networks. Power quality requirements are expected to be stricter than ever before in the future SG. The main inputs for power quality analysis are measurements obtained by monitoring systems. Useful information related to power quality monitoring system projects is available in [8]. Most of the power quality monitoring systems are specialized for the supervision of individual generation or load units. There is a very modest research work dedicated to wide area network-based monitoring of power quality. SG concept opens a new perspective towards wide-area monitoring systems since it relies on modern communication systems. Therefore, communication systems for monitoring of relevant power quality indicators are of great importance for SG.

The Internet of Things (IoT) in the form of smart devices, communication, and application interfaces is the leading technology in the SG vision [9]. Intelligent electronic devices (IED) equipped with modules for mutual and wide-area communication can be used to form IoT systems in SG. Advanced communication and networking technologies are crucial to enable many new monitoring and control functions in SG [10]. IoT-based communication networks have the potential to increase the observability of traditional distribution networks. Various monitoring functions could be achieved with a higher network's observability with some capable of operating in real-time. The Cloud-based communication system is capable to provide real-time monitoring and control functions in SG [11, 12]. SG is expected to have a distribution network operating (DNO) system with an online voltage monitoring function. An online monitoring function could be upgraded to support online monitoring of the most important power quality indicators. Specialized function for online monitoring of selected power quality indicators using a Cloud-based communication system is the main focus of the research in this article.

This article is organized as follows. Section 2 gives a brief overview of the most important power quality indicators, their definitions, and monitoring requirements. The proposed models of the Cloud-based communication system and SG are described in Section 3. Selected power quality monitoring case studies are analyzed in Section 4. Section 5 summarizes the most relevant conclusions of the article.

2. POWER QUALITY

One of the major requirements in the operation of the power system is to maintain its reliability, i.e. the stability of the power quality parameters. Deviations from these parameters have increased in recent times due to the characteristics of the power system and consumers. There are different definitions of the term power quality. IEEE Standard 1159-2009 [13] defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment. Generally, the concept of power quality can be expressed as the measure, analysis, and improvement of the bus voltage to maintain a sinusoidal waveform at rated voltage and frequency. In this sense, power quality can be divided into terms of voltage and current quality [14]. Some of the direct consequences of poor power quality can be identified as: machines and installations overheating and premature equipment aging, problems with relays and switching equipment, measurement equipment errors, reduced production speed, charges for reactive power, data loss, etc. [15].

The assessment of power quality is reflected in the observation of different quality parameters. In this regard, power quality (PQ) indicators can be defined. The major issues of power quality include: wave shape distortion, voltage variations, and electromagnetic interference (EMI) [16]. When the quality of a voltage signal is analyzed, several different PQ indicators of voltage distortion can be pointed out such as: voltage sag, voltage swell, impulsive and oscillatory transient, interruption, voltage fluctuations and flickers, notching, and voltage unbalance [14]. In addition, system frequency deviations from the nominal value, current and voltage harmonic distortions are analyzed. Considering the position of the occurrence in the electric utility system, PQ indicators can be divided into primary or secondary indicators. Indicators related to production, transmission and distribution of the electric power are designated as primary and include voltage variations, power supply frequency variations, voltage dips, power failure, temporary surges, and transients. On the other hand, parameters related to consumer impact are marked as secondary indicators that include harmonics, voltage fluctuations and unbalances [15].

2.1. Standard-based definitions of PQ indicators

For the assessment of the power quality indicators, there are standard-defined relations and tolerances. A frequent occurrence related to a voltage distortion in the electrical distribution system, which is analyzed in this article, is a voltage unbalance. According to [17] unbalance should be calculated using the method of symmetrical components, as the ratio between the negative and the positive sequence component, expressed as a percentage [18]. Total Harmonic Distortion (THD) is defined as a mathematical representation of the harmonic distortion level of voltage and current waveforms. It is equal to the ratio of the RMS harmonic content to the fundamental [17]. THDs for voltage and current distortion are defined by equations (1) and (2), respectively:

$$THD_U = \frac{\sqrt{\sum_{n=2}^{\infty} U^2_{(n)}}}{U_1}, \quad (1)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I^2_{(n)}}}{I_1}, \quad (2)$$

U_1 and I_1 are voltage and current fundamental RMS values. n is the harmonic order number.

Limits for harmonic current emissions (for equipment input current ≤16 A per phase) are given in international standard IEC 61000-3-2 [5]. Further, there are several mathematical relations to evaluate other typical PQ indicators, such as distortion factor or crest factor.

2.2. Monitoring of PQ indicators

For the development of standard procedures in measuring PQ indicators, different editions of the standard IEC 61000-4-30 [19] have been published. According to these, there are classes of measurement systems, depending on the measuring accuracy. Additionally, one of the frequently used standards in developing a monitoring system is IEC 61000-4-7 [20] (instrumentation intended for measuring of the harmonic spectrum, frequency range up to 9 kHz).

Some of the common, main functional blocks of the power quality monitoring diagram are: peripheral signal conditioning circuits, A/D converter circuit, digital signal processing system (DSP), power quality data storage or data upload [21, 22]. Data acquisition at individual points is performed using instrument transformers, with signal filtering and elimination of noise. However, PQ indicators like transient and harmonic components require the use of high-frequency measurements. This also requires a specific memory base. For remote signal processing or data upload, from multiple distribution network points, different TCP/IP communication systems can be used. One of the communication systems of this type is presented in this article.

3. CLOUD-BASED COMMUNICATION SYSTEM FOR SG

The technology progress has led to the modernization of the electricity delivery system, making it smart. SG is an electricity network that uses novel technologies for enhancing the communication, automation, and connectivity of the diverse parts of the power network. As SG consists of various devices (i.e. micro-grids, substations, smart meters, communication network devices), the crucial is to realize the successful two-way and real-time data flow for energy production, transmission, and distribution, control and monitoring, supply and demand balancing [23]. Smart devices applied in the smart grid environment produce voluminous data whose collection and analysis have to be accurate and timely in order to make rapid and correct decisions. Due to limited memory and storage capacity and computation capability of the current power system architecture, handling massive data efficiently and effectively and its analysis are challenging [24]. Hence, the integration of new information and communication technologies in SG is mandatory. Cloud computing, as the next-generation computing and storage paradigm, is an emerging solution to the aforementioned challenges. Cloud computing integration with the SG provides clean, extremely reliable, elastic, distributed and scalable computing resources for hosting SG applications, making them accessible to the customers anywhere and anytime [25].

The cloud services can be delivered in three manners [24]: Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). In this article SaaS function with TCP/IP communication system is used for monitoring and visualization of selected PQ indicators in the SG model.

3.1 MATLAB-based model of IEEE 13 distribution feeder

In this article, the well-known MATLAB-based model of the IEEE 13 Node Test Feeder [26] has been applied for modeling purposes. This test grid was originally meant to test new power flow algorithms in handling highly unbalanced three-phase radial systems and is not intended to present a “full-size” distribution circuit [27]. However, IEEE 13 Node Test Feeder is relatively small in size, but it holds really interesting features. It consists of 13 nodes (Fig. 1(a)), which are interconnected with 10 overhead and underground lines, one generation unit, one voltage regulator unit, one transformer ΔY 115/4.16 kV, one in-line transformer YY 4.16/0.48 kV, two shunt capacitor banks, unbalanced spot and distributed loads. The grid voltage level is 4.16 kV and it is short and enough loaded [28, 29]. A detailed description of the MATLAB-based model of IEEE 13 is given in our previous article [12]. The new scenario-specific modifications in the model are described in Chapter 4.

3.2 Real-time communication system for monitoring of PQ indicators in SG

Simulation of a real-time communication system that enables monitoring of SG has been performed with the help of the open-source IoT platform ThingSpeak [30]. ThingSpeak enables the collection, analysis, and visualization of real-time data streams in the Cloud. It supports real-time communication, allowing two-way information flow between the user and the simulated system. Real-time sharing data and remote control between the feeder model and ThingSpeak IoT platform (Fig. 1(b)) are enabled through the MATLAB/Simulink Desktop Real-time Toolbox. This toolbox requires a real-time kernel that interfaces with the operating system. The Simulink Desktop Real-Time kernel gives the highest priority of execution to the considered real-time executable, allowing it to use the CPU to execute without interference at the chosen sample rate and at the prescribed sample times. After the execution completed, the kernel releases the CPU to run other operating system-based applications that need servicing [31].

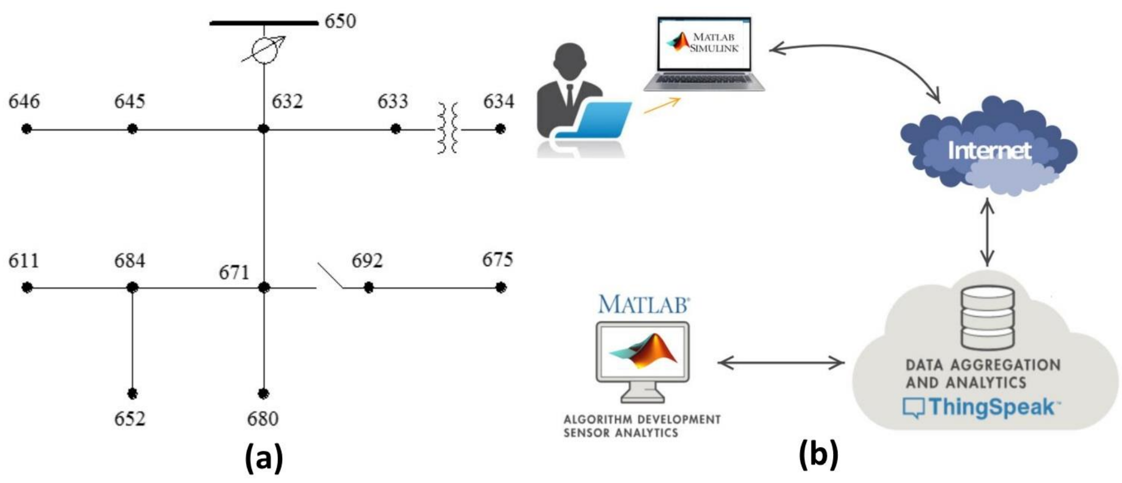

Fig.1 MATLAB and ThingSpeak-based modeling: (a) IEEE 13 Node Test Feeder; (b) IoT communication scheme

The proposed simulation procedure uses the Newton-Raphson method for a load flow analysis of distribution system model. The results of load flow calculations related to selected PQ indicators at desired network nodes are continuously sent to ThingSpeak at 20 s rates in real-time. The monitoring function is achieved using an available online visualization tool.

4. POWER QUALITY MONITORING CASE STUDIES

Specific issues in the field of power quality can be conveniently displayed on the described distribution system. Accordingly, this chapter contains four descriptive scenarios that are relevant to the distribution level of the electric power system.

4.1 Scenario 1 - reactive power compensation

The first scenario of this analysis is the monitoring of reactive power compensation at certain points of the distribution network. Namely, the electrical network typically contains elements that absorb reactive power, as are asynchronous motors, transformers, and other inductive loads. The flow of reactive power can significantly increase network losses and disrupt voltage conditions. Improvement of the voltage profile can be achieved by using different devices such as, insertion of distributed generation, a variation of transformer tap positions or voltage regulators, capacitor or with the application of power electronic devices as are reactive power compensation – SVC, stationary reactive power compensation technology – STATCOM, static synchronous series compensator – SSSC [32, 33].

Scenario 1 describes an example of the individual compensation of reactive power. The load used in this example does not reflect compensation deriving from the symmetrical consumer case and the used capacitor bank is illustrative in nature. For the first case, there is no additional load at node 675. The monitoring system records the data for the calculated load flow, marked as LF1. The case 2 follows and involves an inductive-load condition, when an additional load at node 675 is connected with the following phase loads: P_A = 485 kW, Q_A = 380 kvar; P_B = 68 kW, Q_B = 120 kvar; P_C = 290 kW, Q_C = 424 kvar (load flow 2 – LF2). After the case 2, case 3 registers the load flow for the distribution system condition, when the capacitor batteries at node 675 are switched on (LF3). The power of fixed batteries per phase is 200 kvar.

The voltage profile for scenario 1 is presented in Fig. 2. It can be observed that the voltage variation is dominant for the nodes located in the radial line, in which the additional load is included, in case 2. When the battery bank, of the experimentally adopted value, is switched on, a more suitable voltage profile is obtained. At that point, the voltage values are increased compared to the previous case.

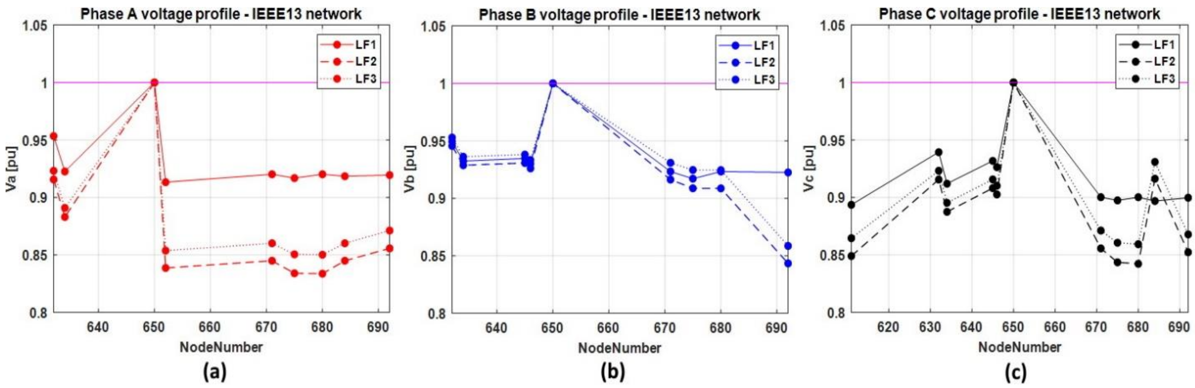

Fig. 2 IEEE 13 network model voltage profile for reactive power compensation scenario:
(a) phase A; (b) phase B; (c) phase C;

Fig. 3 shows recording results, obtained using the analyzed ThingSpeak-based communication system. The real-time monitoring collects data every 20 seconds, which is sufficient to analyze power quality indicators related to reactive power compensation in the distributed system. Measurements are shown for the three different nodes, per phase, and it is concluded that a decrease in voltage level occurs when the inductive load is switched on. In the third part of the signal, switching on the battery causes an increase in voltage level at all nodes, per phase, and this increase is not equal due to the unbalance power consumption of the observed node.

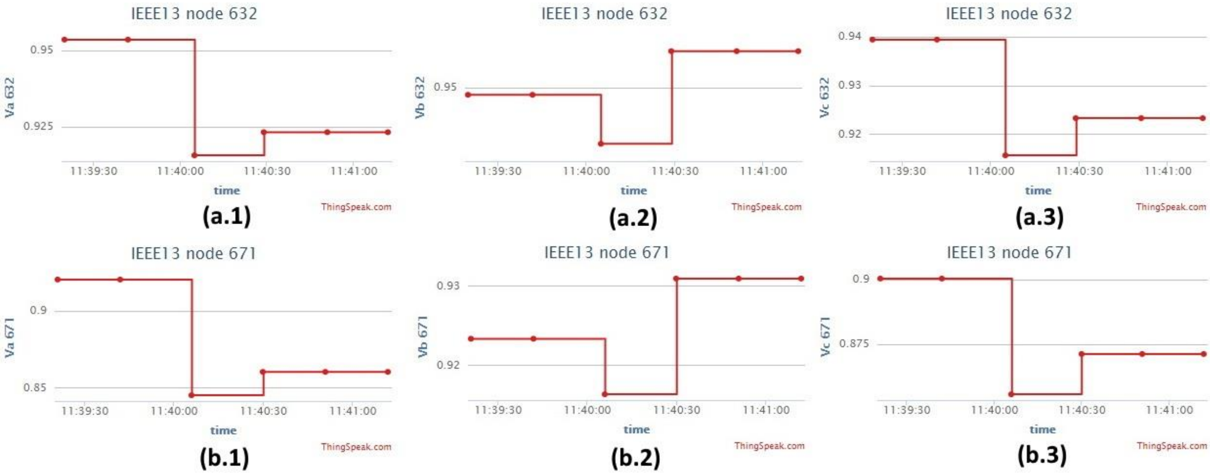

Fig. 3 ThingSpeak-based real-time monitoring of IEEE 13 network model voltage magnitudes for reactive power compensation scenario:
(a) node 632 - (a.1) phase A, (a.2) phase B, (a.3) phase C;
(b) node 671 - (b.1) phase A, (b.2) phase B, (b.3) phase C;

4.2 Scenario 2 - evolving line fault

In the second scenario, the voltage changes caused by the occurrence of an evolving fault at certain phases in the distribution system are simulated. Typical of such events is the appearance of the voltage swell. This occurrence is defined in [13, 14] as an increase in RMS voltage from 110% to 180% of nominal voltage at power frequency for a duration from ½ cycle to one minute. One of the methods to overcome such voltage disturbance is also the use of Dynamic Voltage Restorer device - DVR [34]

As a scenario example, the fault location is in the middle of the line 632-633 length. The scenario is divided into three parts. For case 1 of the monitoring scenario, there is no fault in line 632-633. Power flow is marked as load flow 1 (LF1). A fault in phase A occurs in case 2, between nodes 632-633, with fault resistance of 1 Ω (Load flow 2 – LF2). In case 3 (LF3), the fault evolves and becomes a phase – phase – earth fault (A – B short circuit) with fault resistance of 0.1 Ω (metal fault). The voltage profile of the IEEE 13 network nodes is presented in Fig. 4. Fig. 5 shows the voltage profile monitoring using a ThingSpeak communication system for the considered scenario.

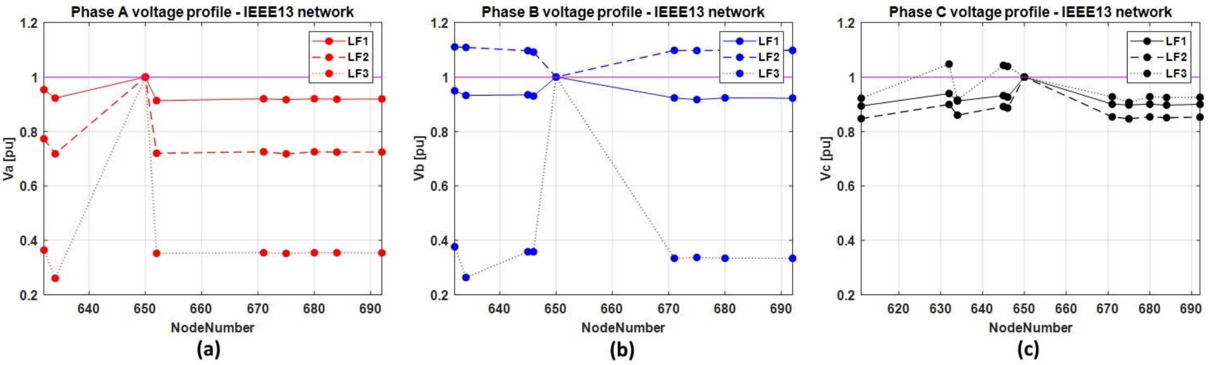

Fig. 4 IEEE 13 network model voltage profile for evolving fault scenario:
(a) phase A; (b) phase B; (c) phase C;

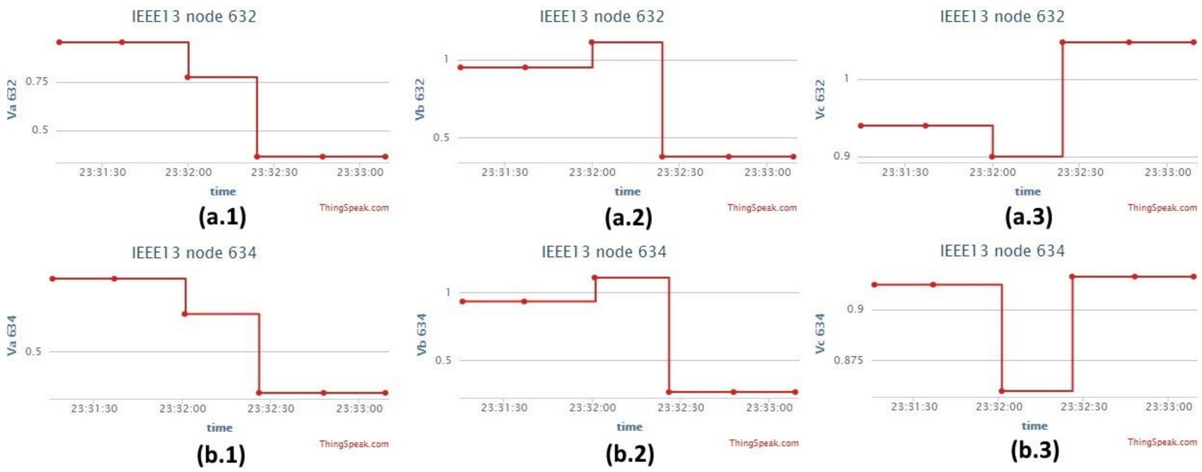

Fig. 5 ThingSpeak-based real-time monitoring of IEEE 13 network model voltage magnitudes for evolving fault scenario:
(a) node 632 - (a.1) phase A, (a.2) phase B, (a.3) phase C;
(b) node 671 - (b.1) phase A, (b.2) phase B, (b.3) phase C;

The characteristic increase of voltage profile for case 2 (LF2) can be seen in Fig. 4 (b). The significant decrease in voltage profile is observed for phases A and B in Fig. 4 (a) and Fig. 4 (b) for case 3 (LF3). The voltage values fall below 40% of the nominal value. The increase of the voltage values can be observed for phase C in case 3 (LF3). Looking at the recorded data on the monitoring system (Figure 5 (a.1), (b.1)) it can be seen that the voltage drop in phase A was observed and recorded for scenario 2. The characteristic increase in the voltage profile for the phase – phase fault, presented in Fig. 4, was also recorded at the nodes 632 and 634, for phase c of the distribution system (Fig. 5 (a.3), (b.3)).

4.3 Scenario 3 - voltage unbalance

One of the common phenomena in the three-phase system is the voltage unbalance, defined as a variation in the amplitudes of the three-phase voltages, relative to one another. This also results in changes in phase angles. It arises as a result of different events in the electric power network, especially in distribution systems, such as single-phase loading, transmission lines that are not transposed, fault in a three-phase capacitor bank, etc [35].

The scenario describing this condition is divided into two cases. In the first one, the voltage at node 680 was recorded on occasions when there is no additional load unbalance. Thereafter, an additional single-phase load (P_A = 200 kW, Q_A = 150 kvar) is switched on, in case 2. For this purpose, a voltage magnitudes and phase angles for the remote node 632 are shown in Fig. 6. They were recorded on a communication system with the 20-second sampling. The voltage unbalance, caused by the additional load, which causes changes in magnitudes, is accompanied by changes in phase angles, as detected by the system. The additional single-phase loading reduced the amplitude in phase A. Description of this event is also given by the monitoring of the voltage unbalance factor, as shown in Fig. 7.

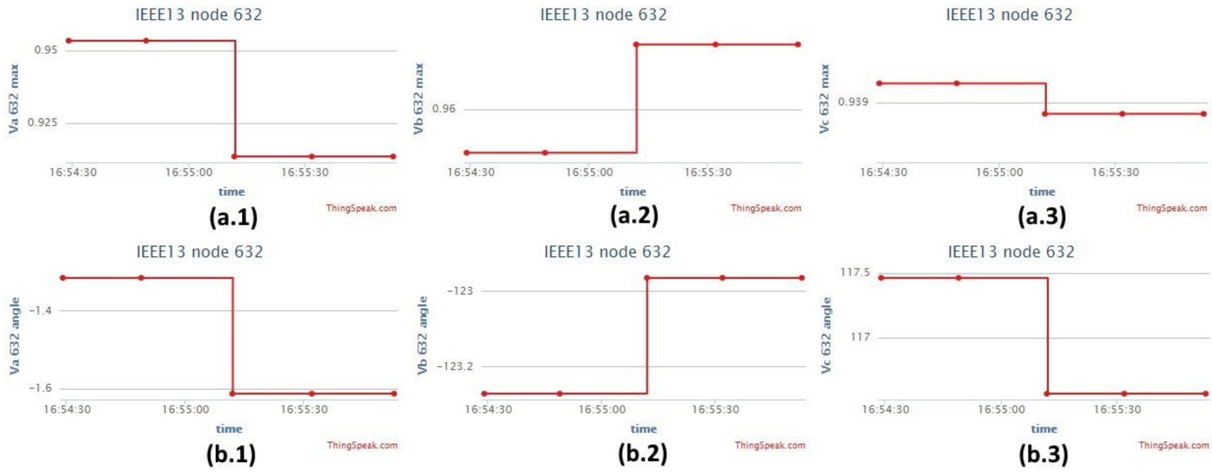

Fig. 6 ThingSpeak-based real-time monitoring of node 632 voltage magnitudes and phase angles for voltage unbalance scenario:
(a) magnitudes - (a.1) phase A, (a.2) phase B; (a.3) phase C;
(b) phase angles - (b.1) phase A, (b.2) phase B; (a.3) phase C;

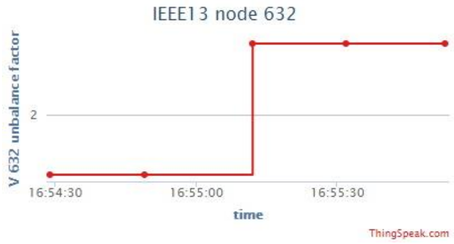

Fig. 7 ThingSpeak-based real-time monitoring of node 632 voltage unbalance

4.4 Scenario 4 - total harmonic distortion

Scenario 4 deals with the impact of personal computer (PC) equipment on the distribution network quality parameters, in terms of harmonic content. For this purpose, the current harmonic content at three nodes is observed, node 634, 632, and 675. At first, there is no additional load in the network (Case 1), and then the PC center load is switched on at node 634 (Case 2). In this sense, the typical load harmonic current content for this scenario is modeled [36]. Timeseries of voltage and current for the PC loading scenario are presented in Fig. 8. These are obtained in time-domain simulation by solving a system of differential equations for the IEEE 13 feeder model. The simulation of THD real-time monitoring with MATLAB requires solving harmonic load flows because the time-domain simulation is significantly slower. This is planned to be solved in future research.

The dominant influence of the current harmonic content is observed at node 634 and 632, for phase A, but for node 675 it is negligible. The real-time monitoring of current THD for PC loading is not achieved, but rather indirect monitoring with corresponding results presented in Fig. 9.

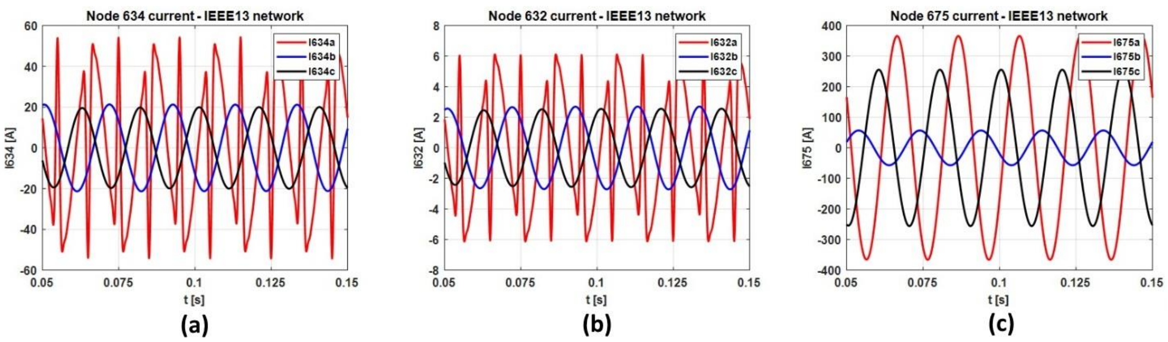

Fig.8 Timeseries of IEEE 13 node currents for PC center loading scenario:
(a) node 634; (b) node 632; (c) node 675;

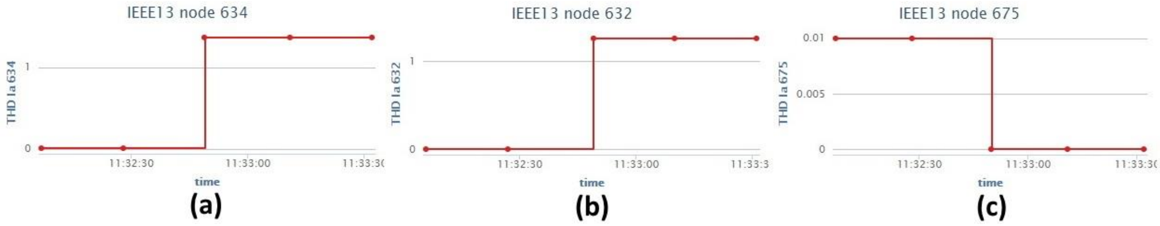

Fig. 9 ThingSpeak-based real-time monitoring of IEEE 13 node current THDs [p.u.] for PC center loading scenario: (a) node 634, (b) node 632; (c) node 675;

CONCLUSION

PQ indicators affect the consumers of a different character. However, they are important for reducing transmission losses and the reliable operation of the power system. Therefore, the assessment of individual PQ indicators is gaining in importance. Recording of PQ indicators information becomes more demanding in SG, given the number of measurement points, from which the status should be monitored, and the amount of data received. Integration of the new technologies in SG, such as IoT-based communication system and Cloud computing could offer great benefits. This article highlights the possibility of real-time monitoring of PQ indicators in SG using the ThingSpeak IoT platform. The proposed monitoring system is tested using a MATLAB-based model of the IEEE 13 distribution feeder. The monitoring system used allows different data to be collected and analyzed from multiple nodes in the distribution system. In order to validate the functional connection of the proposed monitoring system to the distribution feeder model, several different scenarios of power quality events have been analyzed. The potential of the real-time monitoring system is revealed and tested in this research. It is shown that the use of modern communication technology successfully enables the monitoring of various PQ indicators from the observed distribution system. The proposed monitoring system could be used in real distribution systems to collect and analyze wide-area measurements from equipment with TCP/IP communication enabled.

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