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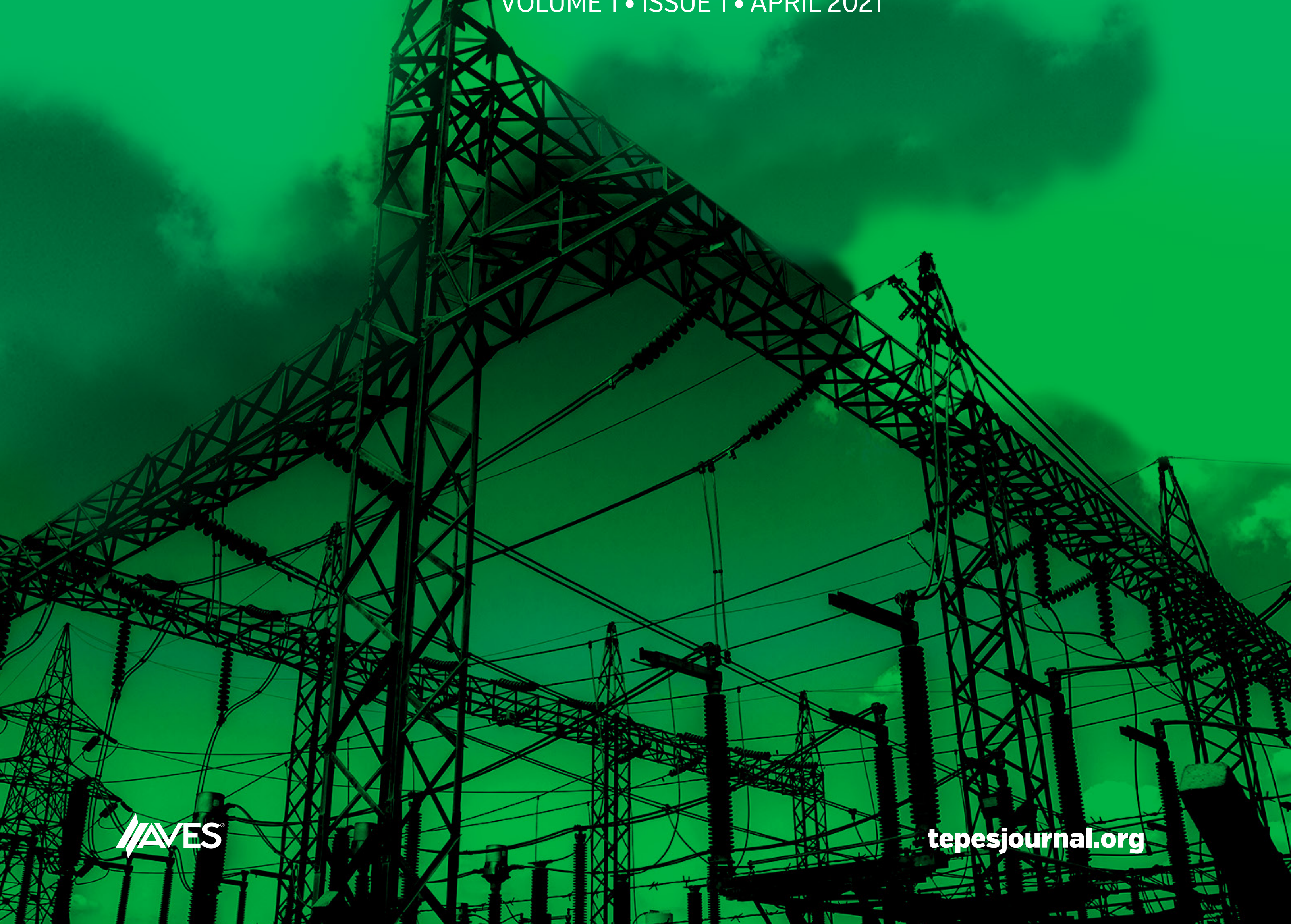

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Table 1. Limitations for each manuscript type

Type of manuscript	Word limit	Abstract word limit	Reference limit	Table limit	Figure limit
Research Article	4000	250	35	6	5 or total of 10 images
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Letter to the Editor	500	No abstract	5	No tables	No media

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Tables should be included in the main document, presented after the reference list, and they should be numbered consecutively in the order they are referred to within the main text. A descriptive title must be placed above the tables. Abbreviations used in the tables should be defined below the tables by footnotes (even if they are defined within the main text). Tables should be created using the "insert table" command of the word processing software and they should be arranged clearly to provide easy reading. Data presented in the tables should not be a repetition of the data presented within the main text but should be supporting the main text.

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Limitations, drawbacks, and the shortcomings of original articles should be mentioned in the Discussion section before the conclusion paragraph.

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Book Chapter: A. Rezi and M. Allam, "Techniques in array processing by means of transformations" in Control and Dynamic Systems, Vol. 69, Multidemsional Systems, C. T. Leondes, Ed. San Diego: Academic Press, 1995, pp. 133-180.

Book with a Single Author: W.-K. Chen, Linear Networks and Systems. Belmont, CA: Wadsworth, 1993, pp. 123-135.

Conference Proceedings: L. Liu and H. Miao, "A specification based approach to testing polymorphic attributes," in Formal Methods and Software Engineering: Proc. of the 6th Int. Conf. on Formal Engineering Methods, ICFEM 2004, Seattle, WA, USA, November 8-12, 2004, J. Davies, W. Schulte, M. Barnett, Eds. Berlin: Springer, 2004. pp. 306-19.

Report: K. E. Elliott and C.M. Greene, "A local adaptive protocol," Argonne National Laboratory, Argonne, France, Tech. Rep. 916-1010-BB, 1997.

Thesis: M. W. Dixon, "Application of neural networks to solve the routing problem in communication networks," Ph.D. dissertation, Murdoch Univ., Murdoch, WA, Australia, 1999.

Manuscripts Published in Electronic Format: P. H. C. Eilers and J. J. Goeman, "Enhancing scatterplots with smoothed densities," Bioinformatics, vol. 20, no. 5, pp. 623-628, March 2004. [Online]. Available: www.oxfordjournals.org. [Accessed Sept. 18, 2004].

Standard: IEC 60060-2 “High-voltage test techniques, Part 2: Measuring systems”, 2010.

Online Document Published in a Web-Site: BIPM, Evaluation of Measurement Data–An Introduction to the “Guide to the Expression of Uncertainty in Measurement” and Related Documents, JCGM 104:2009. [Online]. Available: http://www.bipm.org/utils/common/documents/jcgm/ JCGM_104_ 2009_E.pdf

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REVIEWS

*These papers were presented in ELECO 2020.

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RESEARCH ARTICLE

Importance of Real-Time Hydro Power Plant Condition Monitoring Systems and Contribution to Electricity Production

İzzet Alagöz, Mehmet Bulut, Veysel Geylani, Arif Yıldırım

Electricity Generation Co., Ankara, Turkey

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ABSTRACT

In 2019, 16% of the world's total electricity generation was provided by hydroelectric power plants. Continuity of electricity production can be ensured by monitoring the status of these systems and timely maintenance without causing malfunctions. As hydro turbines typically rotate at a slower speed, they often have to operate at a partial load to meet the fluctuating electricity demands. This partial load process increases the potential for water pressure-related vibrations, turbulence, and cavitation. Continuous operating plant parts are prone to fatigue and damage owing to the excessive vibration caused by these fluctuations. It is possible to ensure that they work in harmony with each other from the smallest parts to large systems using online monitoring systems. This also extends life and increases performance of the power plants because of protected system integrity. In this study, we aimed to examine the importance of real-time hydroelectric power plant condition monitoring and its contribution to electricity generation in detail and presented suggestions for increasing system efficiency.

Keywords: Condition Monitoring, hydro power plant, electricity production, real-time system

Introduction

The use of fossil resources in the production of energy, which has become the main element of the maintenance of life, is high. In addition to increasing external dependency on energy, this brings along with it irreversible/long-lasting damages to the environment. Today, countries are making efforts to lower the use of fossil energy sources to reduce the global warming and greenhouse effect and develop strategies to increase the share of renewable energy sources.

More than 25% of energy needs of many countries worldwide are met from hydroelectric power plants (HEPP). Hydroelectric energy is an important source that provides 50% of the national electricity in 65 countries, 80% in 32 countries, and almost all electricity needs in 13 countries. As of 2019, the installed global hydroelectric capacity is at a level of 1,307 GW, and 16% of the world's total electricity generation in 2019 was provided by HEPPs [1]. In terms of renewable energy sources, Turkey's technical production potential is 216 billion kWh/year from hydropower resources. In addition, it is seen that in today's conditions, Turkey has a potential of 128 billion kWh/year that can be reached both technically and economically and has a great hydroelectric potential waiting to be evaluated. Turkey's 31.8% of the total installed capacity constitutes HEPPs with 29,916 MW installed capacity value [2]. It is notable that hydraulic power plants producing 88.8 billion kWh of electricity were operated efficiently with minimum failure for continuous production in 2019. This was achieved by monitoring the HEPPs properly and managing them efficiently.

Monitoring the operating condition of the bearings in a hydropower unit is a vitally important component of overall facility maintenance and reliability program. Direct monitoring and analysis of the power plant condition, especially the monitoring and analysis of the vibration condition, gives a good idea about the utilization status of hydraulic turbines and enables efficient maintenance operations [3]. In a condition monitoring (CM) system, only data recording and visual curve monitoring is not sufficient. It is necessary to increase the accuracy of diagnosis and predict anomalies using smart diagnostic methods. To achieve this goal, the application of artificial neural networks or the use of artificial intelligence methods increases the reliability of the diagnostic process.

In addition, a joint decision tree can be created for anomaly diagnosis between systems located in different geographical locations

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by remotely monitoring the status of different hydraulic power plant turbines. Thus, it is possible to increase the probability of diagnosing problems in remote monitoring of hydraulic power plant turbines [4].

In this study, the parameters and applications used in real-time HEPP condition monitoring were examined, and recommendations were made to increase the contribution of these systems to electricity generation and system efficiency.

Condition Monitoring Systems and Hydropower Plant (HPP) Applications

Today, it is imperative that operational safety of the machines and hydraulic turbines are protected against mechanical vibrations, and their reliability is high to ensure continuous production. CM systems have features, such as measuring mechanical vibrations of machines and determining different amplitudes of these vibrations.

The online monitoring systems include:

- Rotor, shaft, and behavior of rotating parts are monitored.
- Foundation, concrete structure, body, and physical changes that may occur in fixed parts are monitored.
- The frequency of malfunctions that may occur in a machine is detected and diagnosed and maintenance processes in terms of machine health are put in place.
- The EN 13306 maintenance management strategic approach ensures that maintenance activities are handled with predictive maintenance (PdM) approach.

CM serves to track changes in all parameters within a structure and provide specific detailed metrics on how far the unit is from optimum function. Machine health monitoring provides plant operators the information needed to predict when, where, and how to perform maintenance to keep the plant operational; and eventually increases efficiency and revenue and reduces downtime. Being aware in advance when a piece of equipment is approaching failure allows plant personnel to plan repair/replacement, order parts, and schedule manpower.

CM applications are widely used in wind turbines, power transformers, asynchronous motors, gas turbines, and HEPP units that generate electrical energy. The value of a HEPP depends on the successful operation and functionality of all of its connected parts. Each unit poses an element of manageable risk and requires some form of monitoring to reduce this risk and protect the welfare of the facility. To protect these components from future failures and keep them at optimum operating levels, it is essential to use systems that allow power plant operators to monitor the condition of their bearings, shafts, and other parts when the turbine-generator units are running. These systems are designed to monitor a variety of variables including vibration, lubrication and oil thickness, alignment, temperature, and more.

Main Points

- Online condition monitoring in hydropower plant operation can be improved, and significant savings in maintenance costs can be achieved.
- Online monitoring systems maintain system integrity in hydraulic power plants and ensure that they work in harmony with each other.
- It is possible to maintain the functionality of the plant by extending the life of the equipment using condition monitoring systems.
- If online condition monitoring system of a hydroelectric power plant is operated actively, machine downtime is decreased and profits increase.

Causes of Malfunctions in Hydroelectric Power Plants

During the production of electrical energy in HEPP, the turbines are exposed to constant stress caused by starting, stopping, and partial loading. These processes inevitably lead to material fatigue and equipment damage. A fully functional installed CM system helps prevent or at least reduce the damage caused by the daily operation of the machines.

HEPP turbines are sensitive to multiple parameters that continuously reduce their lifespan. Mechanical forces, material destruction, mechanical crushes, large differences in temperature, cavitation, corrosion, and chemical forces can cause various types of damage in power plants. Over the past decades, many HEPPs have switched from continuous base load operation to periodic and partial load operations. This periodic operation has proven to be more cost effective from an economic point of view; however, it adds additional burden to production units owing to the increased start/stop frequency.

As a result, there is a need to implement an effective CM solution to ensure that incipient faults are detected in a timely manner to avoid major damage and resulting downtime. In Figure 2, the most common malfunctions in the generators of hydraulic power plants and the root causes initiating these malfunctions are given [5].

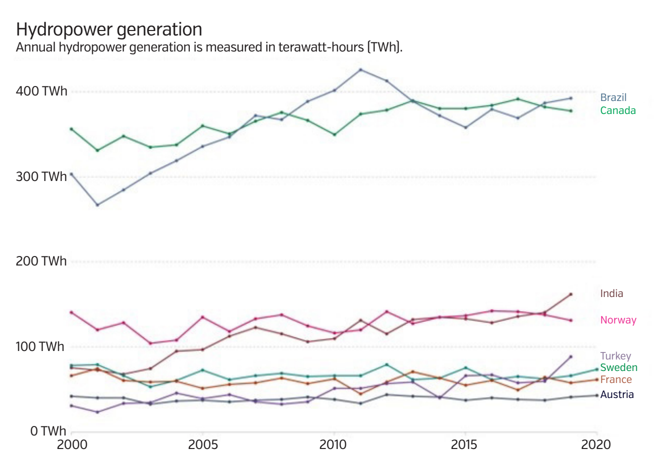

Figure 1. Annual production values of countries that produce the most hydroelectric power worldwide after China (Source: www.ourworldindata.org)

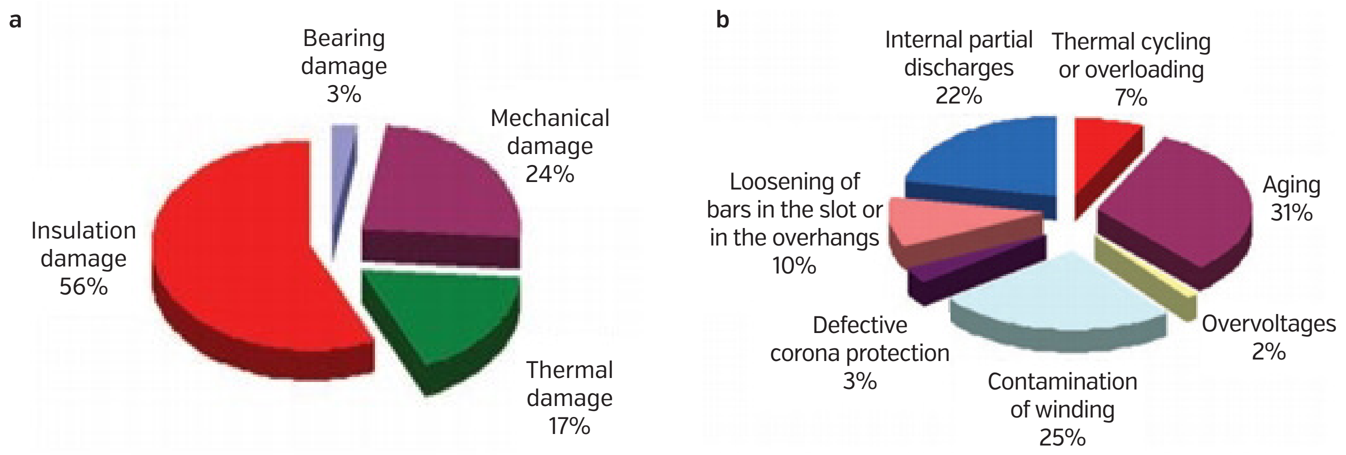

Figure 2. a, b. (a) Damages to hydro generators and (b) root causes of failures [5].

It should considered that all these failures in hydraulic power plants are generally of a slow developing nature. Faults in hydro power plants can be divided into rotor and stator problems.

Rotor problems:

- Change in the positions of the poles,
- Looseness in the rotor ring,
- Deformation in the rotor ring,
- Misalignment in the rotor rotation center.

Stator problems:

- Expansions in concrete (alkali aggregate reaction),
- Stator anchor bolts do not allow thermal expansion,
- Decomposition of stator core and frame.

As the total operating time of the plant increases, expansion and cracking owing to the reactions that may occur in the concrete to which the unit is attached will also cause static eccentricity as it will affect the shape of the stator. The magnetic imbalance in the generator because of static eccentricity causes the shaft to be pulled toward the side by magnetic forces where the air gap is low, together with increase in excitation voltage [10].

Therefore, excessive load can be placed on the bearings, and friction may occur owing to eccentricity in the warning part. Because of machine vibrations and because of the shaft sliding in one direction, the relative shaft vibration sensors in the generator bearings can also be damaged by rubbing against the shaft. As a result, the energy production efficiency of the unit decreases.

Condition Monitoring Systems in Hydroelectric Power Plants

The heart of a typical HEPP is the turbine. Water travels near the turbine runner when passing through the penstock on its way from the reservoir toward the outlet. The flow of water causes the slide blades to rotate and thus the turbine shaft to rotate. The turbine shaft then rotates the generator shaft, creating electricity. Using sensor data collected from turbine components (for example, gearbox, generator, bearings, blades, etc.) can enable predicting malfunctions and to resolve them before they happen as the maintenance program developed using these data ensures that the important components that make up the system are programmed to maintain their health. Furthermore, this will also ensure the implementation of an efficient maintenance strategy [6].

Continuous measurement and monitoring of important parameters gives the opportunity to set warning alarms beforehand. By controlling these parameters, part-specific, generator, and turbine-specific malfunctions can be prevented. Using CM systems in an HEPP, the plant management has an idea of the machine's condition and can make a proper plan or program for replacement. Vibrations are one of the most important values observed by monitoring systems. In all major unit parts, they are also traced in the form of radial relative movements of the shaft relative to the bearing housing in two axes that are rectangular to each other. Absolute vibrations are usually monitored by piezoelectric sensors. However, technological advancements have made optical measurement of vibrations possible.

The vibrations alone are indicative, but not sufficient for the exact assessment of the equipment's conditions. Therefore, it is necessary to monitor other parameters that are important in detecting faulty conditions in the machine, as follows [7]:

- **Vibration** in the form of radial relative movements of the shaft relative to the bearing housing in all major unit parts and in two axes that are rectangular to each other,
- **Rotational speed** measured by an inductive sensor and a marker used as a synchronization probe for individual measurement,
- **Clearance and magnetic induction in the stator core** to identify the eccentricity and asymmetry as well as short circuits between turns on the rotor and stator,
- **Shaft currents and voltages** that can damage the bearing,
- **Load angle** during operation because of control and maintenance of stability,

- **Partial discharges** to monitor winding insulation and detect related problems,
- **Optical measurement of temperature** in HV equipment as well as temperature in stator core and bearing,
- **Hydraulic values** in initial line pressures, levels, and flows that give data on turbine operating parameters as indicator of deviations in the reference operating parameters of the generator,
- **Cavitation** that can cause increased wear of machine parts.

Hydroelectric Power Plant Condition Monitoring Sensors and Parameters

The main task in a hydraulic turbine unit is monitoring the situation, protecting the facility, and early detection of a malfunction [8]. Advanced control systems found in hydraulic power plants typically include the control of the following sub-systems:

- Vibration,
- Partial discharge (PD: Partial discharge - monitoring),
- Magnetic flux generator,
- Air gap (between rotor and generator stator),
- Required temperature and process parameters.

CM standards, which are widely used in hydraulic power plants, include the following techniques:

1. Vibration
2. Infrared thermography
3. Acoustic emission
4. Ultrasonic
5. Tribology and oil sample analysis

The main parameters in the continuous monitoring of the turbine-generator group in HEPPs are given in Figure 3. The sensors and parameters commonly used for CM in hydraulic power plants are:

- Vibration in bearings,
- Bearing oil thickness,
- Cavitation,
- Vortex rope turbulence,
- Generator air gap and magnetic flux,
- Turbine speed and brake system,
- Temperature in high voltage areas.

Online CM software is used to measure mechanical vibrations in the machines with the PdM approach of maintenance activities and to monitor other condition analysis parameters and to evaluate these detected anomalies. Figure 4 gives a typical CM system program user interface.

Air Gap Sensor

The generator belonging to the hydroelectric unit has the components shown in Figure 5. Rotor poles rotate mounted on the rotor ring, which is connected to the shaft by means of the rotor. There is a circumferentially uniform "air gap" between the stator wall where the windings are located and the poles. Many systems are designed to monitor the condition of hydroelectric turbine-generators. The air gap, which is a measure of the distance between the rotor and the stator, is critical information for the life of a hydroelectric generator. A non-concentric rotor and stator can cause

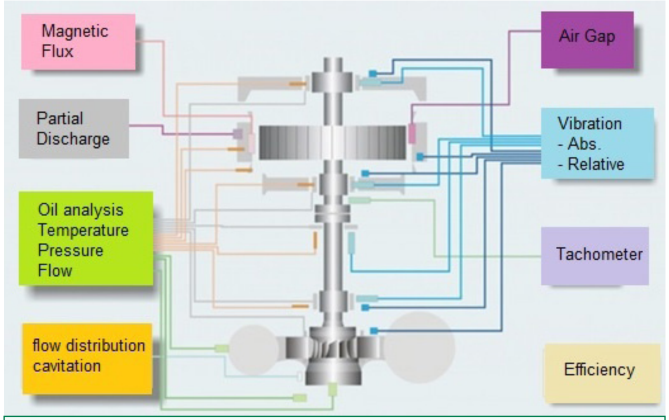

Figure 3. Parameters of the turbine-generator group in hydroelectric power plants.

various problems in the generator that can lead to damage and inefficiencies to key components.

Any change of the relative position between the rotor and the stator will cause the air gap to change, and this change will affect the mechanical, electrical, and thermal balance of the generator [10]. There are many types of malfunctions that can cause a change in the nominal air gap determined in the design of the unit. The air gap measurement allows operators to monitor rotor and stator shapes, positions, and minimum air gap dimensions. It provides operators with the information needed to shut down the machine before serious damage, such as magnetically induced overheating or rotor-to-stator friction.

Air gap sensors can be placed in the upper and lower levels of the generator (Figure 6). It is suggested that the upper-level air gap sensor should be mounted starting from the upper limit of the stator wall just below vent hole 2. In this way, the sensor will be deep enough to detect the smooth surface of the rotor pole. Generally, non-contact type sensors operating on the capacitive principle are used for the air gap measurement.

Vibration Monitoring Instrumentation

Hydro turbines typically rotate slowly at an operating speed of 75 to 1,000 rpm. Turbines often have to operate at partial load to meet fluctuating electricity demands. This partial load operation can increase the potential for water pressure related vibrations, turbulence, and cavitation. Prime mover components are prone to fatigue and damage owing to vibration caused by these fluctuations. In addition to bearing components, turbine and generator shafts and bearings are also prone to excessive vibration. These vibrations may be the result of imbalance, misalignment, bearing fatigue and/or overload, and insufficient bearing lubrication.

The main sources of vibrations occurring in hydro power plants are given below:

- Vibrations caused by electrical fluctuations,
- Mechanical vibrations,
- Vibrations based on hydraulic change.

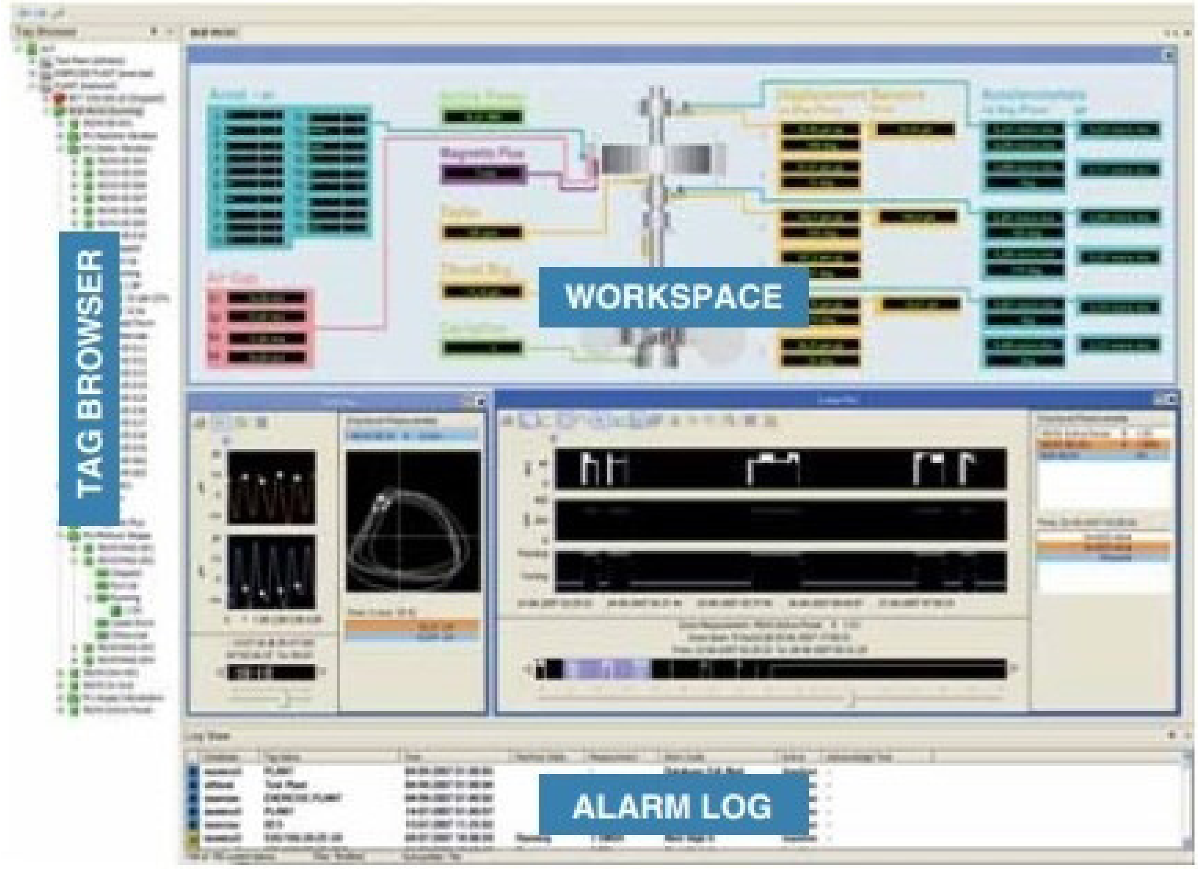

Figure 4. A typical condition monitoring system program user interface.

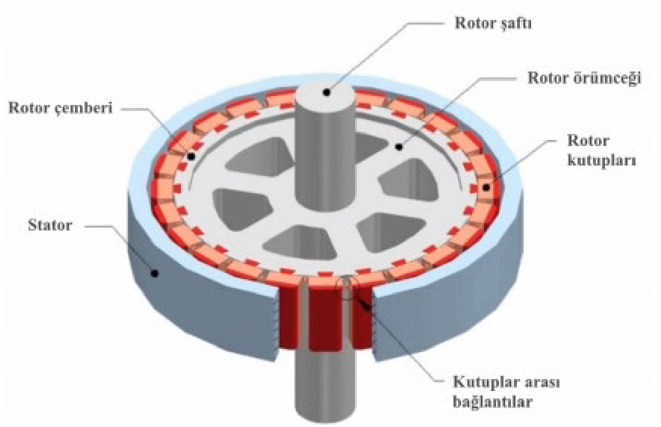

Figure 5. Hydroelectric generator components [9].

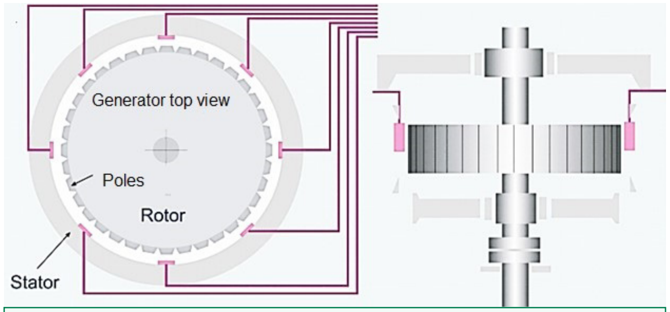

Figure 6. Layout of air gap sensors on the generator [11].

The vibrations occur not only in rotating equipment but also in equipment that do not rotate because of its spreading nature. The vibrations of the hydraulic turbine are caused by excessive force fluctuations caused by cavitation [12].

Bearings play a complex but integral role in the operation of an HEPP and are found in a variety of locations, including:

- Guide bearings both above and below the generator,
- Thrust bearings under the generator,
- Guide bearings in the turbine unit.

Although relatively small in size, a malfunctioning bearing can cause plant shutdown and damage to other valuable components of the plant, including the turbine unit. Defective bearings are caused by normal erosion during use. Machine speed affects the process of finding bearing faults using vibration signals as bearing condition deteriorates. Vibrations in bearing housings may decrease as the failure approaches.

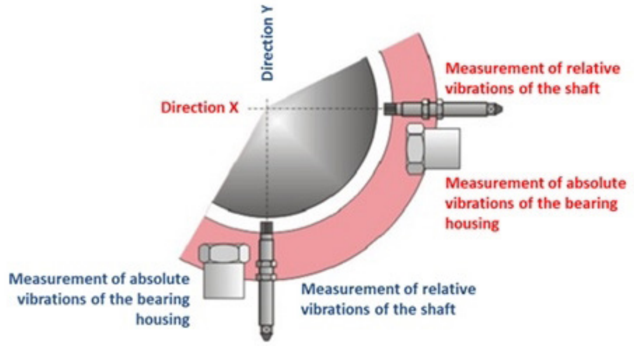

Figure 7. Typical arrangement of vibration sensors

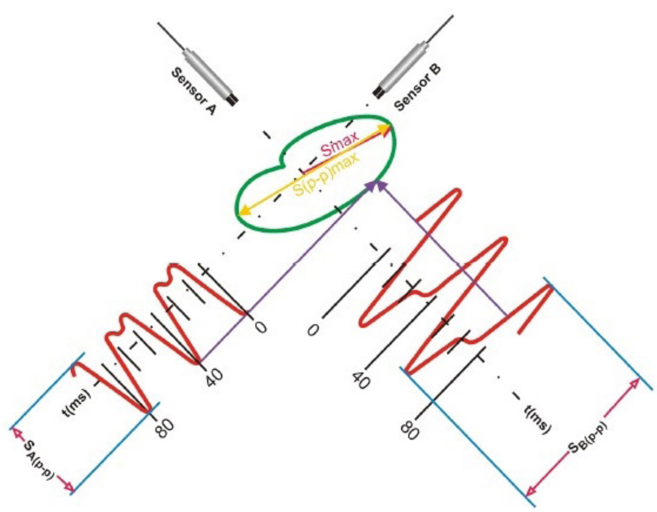

Figure 8. S(p-p) and Smax measurements with double displacement sensor.

Incorrect lubrication of mechanical parts with improper lubrication system parameters causes turbulence of the oil film and results in destruction. According to the statistics given in the literature, approximately 60% of bearing damages are because of improper lubrication. In the lubrication of bearings; suitable oil, suitable lubrication method, appropriate amount, appropriate re-lubrication, and clean oil are factors of great importance [13].

The safe operating condition of HEPPs is based mainly on vibration monitoring. Permanently installed equipment is used to measure overall vibration values at all measurement points at the same time. This type of monitoring equipment creates an alarm and shuts down the machine before a catastrophic failure occurs. As most hydropower equipment has plain bearings, the most effective way to monitor the machine is to measure the vibration relative to the shaft via two displacement probes per bearing plane [Figure 7].

The ISO 7919-5 standard provides recommendations for equipment type, what to measure, where to measure, and acceptable vibration levels for evaluation. The ISO 20816-1:2016 standard specifies the general conditions and procedures for measuring and evaluating vibration using measurements made on rotating, non-rotating, and non-reciprocating parts of all machines. First, when minimizing the negative effects of vibration on the relevant equipment, the aim is to ensure reliable, safe, and long-term operation of the machine [14]. ISO 10816-5 covers Mechanical Vibration - Evaluation of machine vibration with measurements made on non-rotating parts - Part 5: Machine tools in hydraulic power generation and pumping plants [15].

Methods

HPP Condition Monitoring Applications

Application of Relative Shaft Vibrations

The method to monitor and evaluate vibrations in turbines in HEPPs and machine groups in pump stations is described in ISO 7919–5 and ISO 10816–5 international standards. In the measurement of relative shaft vibration, vibration displacement sensors mounted between the shaft and bearing are used in radial bearings; whereas in absolute bearing vibration, sensors that measure vibration acceleration (or velocity) are mounted on the machine block [Figure 8].

The evaluation of the vibrations of hydroelectric machines using relative measurements taken in the radial direction between the bearing and shaft is performed according to the ISO 7919–5 standard. Measurements made within the scope of this standard are called "relative shaft vibrations" and are measured in terms of displacement. Relative shaft vibrations defined in the standard as measured using displacement sensors that are placed radially at an angle of 90° to each other and measure the relative displacement between the bearing and shaft. These sensors do not come into contact with the shaft, and they work on the basis of the eddy-current principle.

Evaluation Zones for Relative Shaft Vibration Measurements

With the standard, the recommended vibration-rating zones for the nominal rotation speed of the machine and stable operating conditions are defined as follows:

- *A-B Major Zone:* Machines whose vibration levels fall in this major zone are considered suitable for long-term operation without restriction.
- *C-D Major Region:* Machines falling in this major region have high vibration levels. The measured values should be checked for their suitability for long-term continuous operation, considering the machine-specific design and operating conditions.

In all cases, relative shaft vibrations should be evaluated by comparing parameters of the bearing diametric clearance and oil film thickness during operation. Tables showing vibration evaluation zones in the standard are given separately for Sp-p (Peak-Peak) and Smax measurements [Table 1]. The standard also mentions the factors to be considered when determining "ALARM" values and "TRIP" values.

- *ALARM (warning):* It was stated that values may vary from machine to machine and that the ALARM level could be deter-

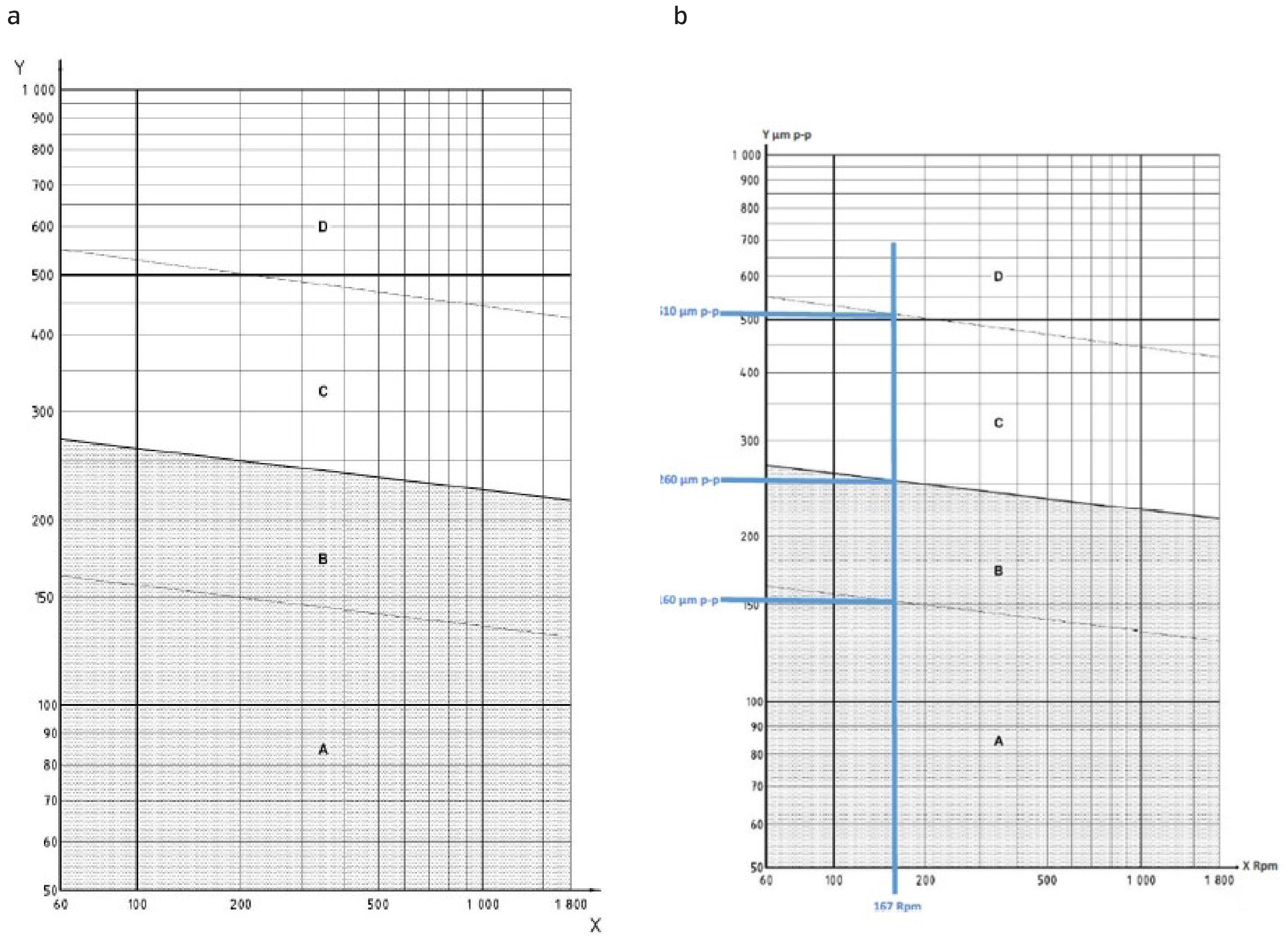

Figure 9. a, b. (a) Table of vibration-rating zones in standard (b) table equivalents of the measurements made in hydro power plant (X: Speed of rotation [rpm], Y: Relative vibration level [µm peak-peak])

Table 1. S(p-p) Vibration evaluation zones included in the standard

Limit values ISO 7919-5		
Limit Name	**Region Definition**	**S_{p-p}(µm)**
Limit A/B	Green Region	160
Limit B/C	Yellow Region	260
Limit C/D	Red Region	510

mined by adding up to 25% of the upper limit value of the A-B major region on the baseline observed under normal operating conditions of the machine. The alarm level determined should not be more than 1.25 times the upper limit value of A-B major region. Depending on the dynamic load condition and bearing stiffness, different alarm levels can be determined in different measurement points and directions in the same machine.

- *TRIP (danger)*: It is stated in the standard that the values will generally be in the C-D major region and should not be more than 2 times the upper limit value of the A-B major region. Considering the experienced data, the µm Smax TRIP level to be determined in the radial bearings should not exceed 85% of the radial bearing clearance value of the bearing to prevent the oil film from being distorted and the shaft from rubbing against the bearing.

In the measurements made in ABC-1 HEPP, the relative shaft vibration assessment has been compared according to the shaft rotation speed of 167 rpm, and the corresponding limit values are shown in Figure 9 and Tables 2 and 3.

When the displacement, orbit, and FFT graphics taken from unit 1 are evaluated, it is seen that the unit operates below the limit value of the A-B major region from the peak-peak vibration evaluation zones given in ISO 7919–5; therefore, in the A region. There were no drawbacks in the long-term operation of this unit, which works in Zone A. Results from the measurements made in hydro power plant are shown in Figure 10.

Table 2. Absolute bearing vibration measurement values taken from Unit 1

Absolute Bearing Vibration Measurement Values					
Unit load status	**Vibration measurement unit**	**Combined bearing**		**Turbine guide bearing**	
147.54 MW	mm/s RMS	CH 1 X	CH 2 Y	CH 1 X	CH 2 Y
		0.234	0.271	0.317	0.289

Table 3. Relative shaft oscillation values taken from Unit 1

Relative Shaft Oscillation Values					
Unit load status	**Vibration measurement unit**	**Combined bearing**		**Turbine guide bearing**	
		CH 1 X	**CH 2 Y**	**CH 1 X**	**CH 2 Y**
147.54 MW	µm (p-p)	149.7	112.9	124.7	98.61
	1X (So-p)	62.56	29.64	35.81	29.82

Condition Monitoring System Hydroelectric Power Plant Application Results

In this section, information is given about the CM system applied in ABC-1 HEPP with an installed capacity of 600 MW. In this system, relative displacement sensors, which can be used in the frequency range of 0–10,000 Hz and temperatures up to 110°C, and vibration speed sensors that can measure up to 2,000 Hz are used. The location, types, and placement of the sensors used in the system are given in Figures 11-13.

When the units of the applied power plant have a power of around 60 MW, the values taken from the CM system used are shown in Figure 14. The measurement parameters displayed in the CM system used in this application are given below:

- Relative shaft vibration, Smax (µm)
- Absolute bearing vibration (mm/s RMS)
- Relative displacement sensor spacing (gap) (mm)
- Relative displacement sensor gap voltage (V)
- Amplitude and phase values for first, second, third, and fourth harmonics of the vibration
- Cycle speed (r/min)

Contribution of Condition Monitoring to HPP Electricity Production

The advantages of real-time monitoring of production equipment in HEPPs can be listed as follows:

- Operation and maintenance costs are reduced.
- Risks to personnel are reduced.
- Equipment can be changed on the basis of system parameters.
- Major malfunctions that cause downtime can be minimized.
- The life and efficiency of the equipment can be improved.

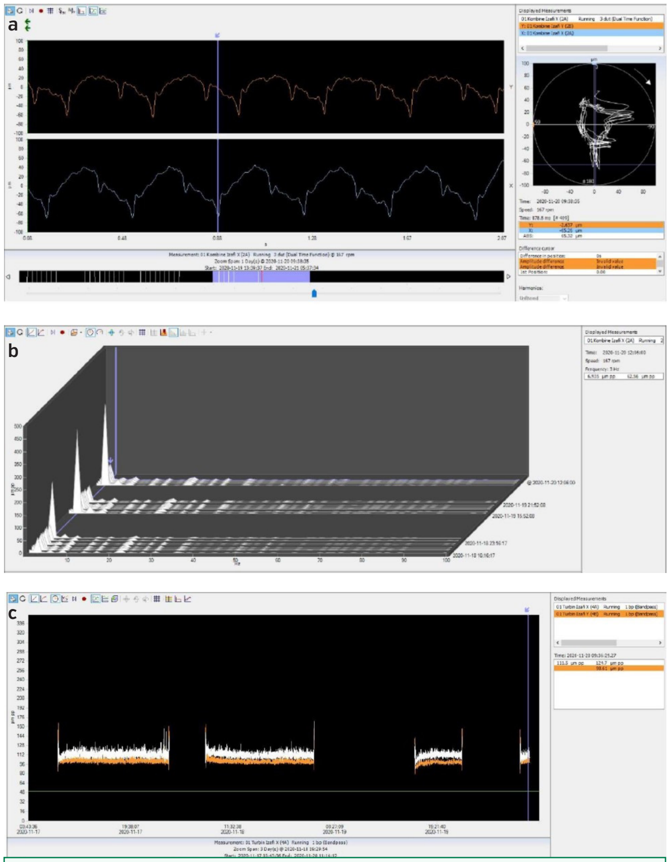

Figure 10. a-c. Display of the results from the measurements made; (a) Relative vibration level in X-Y directions (µm peak-peak) and Orbit plot; (b) Relative shaft spectra in X-Y-Z direction; (c) Relative vibration level changes

- The frequency of downtime can be minimized.
- The machine can be operated within vibration limits.

If the online CM system of an HEPP is operated actively, the cost benefits listed below can be taken according to the reliability of the system [16]:

- Maintenance cost decreases by 50%–80%,
- Equipment failure decreases by 50%–80%,
- Machine downtime decreases by 50%–80%,
- Overtime cost decreases by 20%–50%,
- Machine life increases by 20%–40%,
- Profit increases by 25%–30%.

As an example of the contribution of CM systems to electricity generation in hydraulic power plants, the results of a study carried out in a hydraulic power plant within EUAS can be given. In the hydraulic power plant belonging to Elektrik Üretim A.Ş, which has four vertical axis Francis type turbines with a capacity of 167.4 MW each, a failure of the unit to be kept not available owing to the generator oscillations occurred. The behavior of the generator shaft caused magnetic unbalance because of variable magnetic charge interactions when the current unit was operating.

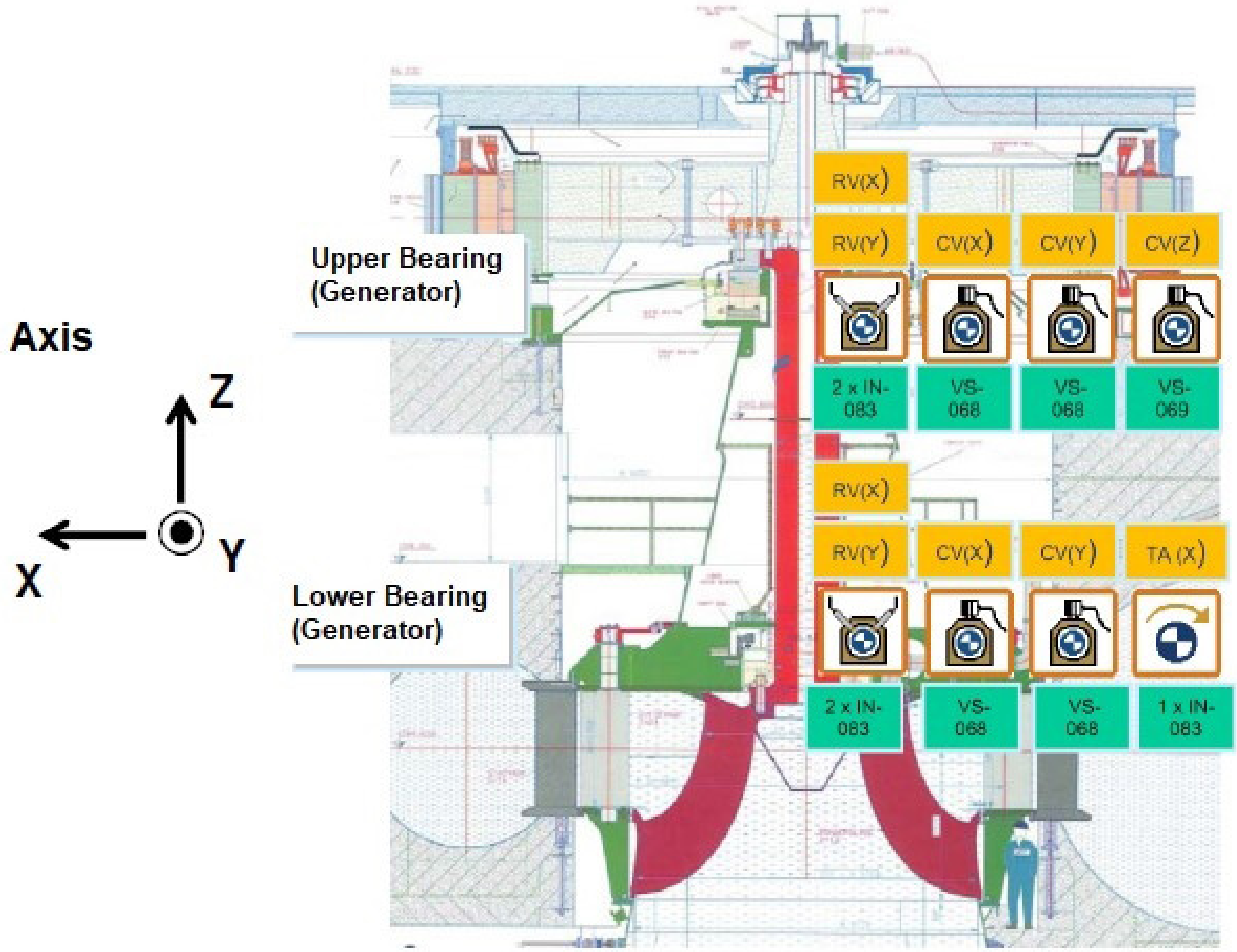

Figure 11. Placement of sensors used in the system.

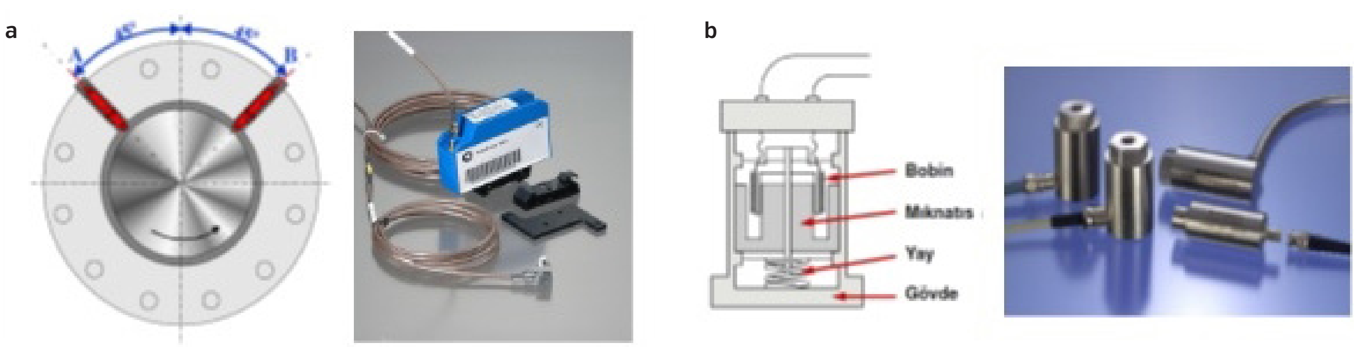

Figure 12. a, b. Relative displacement and vibration speed sensors used in the system. (a) Relative displacement sensor, (b) vibration speed sensor.

To eliminate the main problem causing high emissions, the absolute and relative shaft behaviors of the generator have been demonstrated by monitoring the vibration measurements and relative shaft measurements from the fourth unit generator upper guide-bearing areas. Balancing studies have been conducted to dampen the centrifugal forces that cause magnetic unbalance and cause the unit to oscillate excessively. The unit was loaded at 140 MW from the warning position and operated for 6 h from 9:00 to 15:00 (hot position). Oscillation was observed to be at the level of X 185, Y 211 microns. To eliminate the main problem causing high emissions, bed vibration measurements, and balancing application studies have been carried out. Relative shaft oscillations have been brought to the transition zone from the good to the sufficient machinery zone in the quality class in ISO 7919-5 international standards. To evaluate the results of the work carried out, the unit was kept available for six months and operated according

Figure 13. Placement of the sensors used in generator and turbine bearings

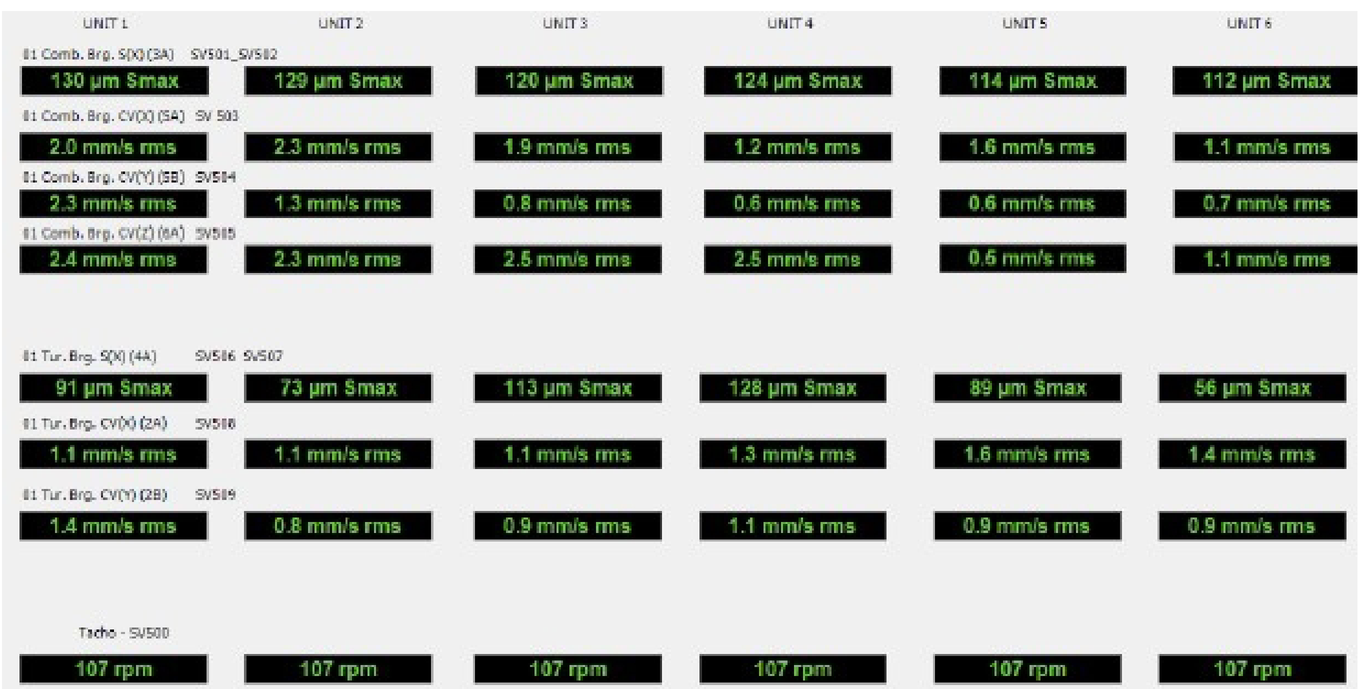

Figure 14. User interface of the information from the condition monitoring system used in the system.

to the daily production schedule consistent with the needs of the system.

The vibration was monitored from the online system for predictive maintenance operations while the unit was running. Because of the unit being on hold for a long time of vibration, it caused both production and discharge of water from the spillway during the flood period. As a result of determining the problem in the generator using CM method and solving the problem, a total of 245.3 million kWh electricity was generated from the fourth unit of the hydraulic power plant between May 28-May 30 and December 20, 2019.

Discussion

Online monitoring systems, which are widely used in the industry, especially in critical equipment, are of great importance in reducing maintenance costs, minimizing machine downtime, and preventing disruptions in production. In particular, online monitoring systems powered by artificial intelligence modules play a major role in making diagnosis of machine faults faster. With the integration of Enterprise Resource Planning software, it provides support for important inputs of maintenance planning at the point of tracking stocks of machine spare parts and faster procurement.

There has been a huge amount of application of cloud technologies in recent times. It provides rapid access to online monitoring data and the establishment of data infrastructure. It helps experts from different centers to analyze data required for fault diagnosis. Similarly, with the use of modern technologies and innovative methods for the maintenance of HEPPs, the cost can be reduced, the plant's reliable production can be increased, and long-term interruptions can be minimized. Turbine wheel and generator are the most important equipment in an HEPP. CM system, which includes parameters such as real-time online vibration monitoring, continuous air gap measurement, online partial discharge measurements and stator-winding isolation facilitates the abovementioned benefits.

In this study, the structure of a real-time HEPP CM system was examined, and its contribution to electricity generation was presented through an example by giving their applications in hydraulic power plants. It is concluded that if the operation and maintenance are optimized according to the actual characteristics of the turbine, generator, and other important equipment of the plant; the profitability and reliability of the hydropower plant operation can be improved, and significant savings in maintenance costs can be achieved. Online monitoring systems maintains the system integrity in hydraulic power plants and ensures that they work in harmony with each other, from the smallest component of the power plant to the largest components such as turbines and generators. Thus, it is possible to maintain the functionality of the plant by extending the life of the equipment.

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RESEARCH ARTICLE

Power Quality Evaluation of Distributed Generation Systems

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ABSTRACT

Effective and efficient use of power systems is directly related to the quality of the distributed power. Power quality should be monitored, and various analyses should be made to provide full control over the network. The importance of the power quality is clearly understood when the number of consumers in distribution systems is considered. When handling the distribution systems, it is seen that the distributed generation resources (DGS) may have positive and negative impacts on power quality. Increasing the presence of DGSs in power systems requires evaluation of their effects on the network. In this study, we aimed to examine the effects of DGSs on power quality through indices. The response of the power quality before and after the integration of distributed generation into the distribution system was evaluated using voltage variation and total harmonic distortion (THD) indices. Various simulation studies have been carried out on a real test system at different harmonic levels for THD, voltage variation, related power quality variation indices, and system indices for THD to be calculated. It has been observed that the indices considered are important to analyze the power quality of a distribution network in the presence of DGSs. The results show that the impact of harmonics and voltage drop can be reduced with properly located and increased rated power of DGSs.

Keywords: Distributed generation, voltage variation, power quality, power quality indices, total harmonic distortion

Introduction

With the rapid development of the industrial sector, there is an increase in power consumption, which will continue to rise. This development might lead to an increase in power quality problems. Therefore, it is very important to identify and deal with these problems.

Today, reasons such as decrease in fossil energy sources, increase in the number of consumers, and negative effects of traditional energy sources on the environment have increased the interest in alternative energy sources. With an increasing interest in these resources, the concept of distributed generation has emerged. The term "distributed generation" is used for generation resources below 10 MVA connected to the power system from the distribution network [1].

Distributed generation shows both positive and negative effects on power systems, which are widely found in the networks. Distributed generation can cause power quality problems that can have significant effects. These problems include voltage fluctuations caused by the change in the output power of the generator in distribution networks, imbalances caused by single-phase generators, and temporary impacts such as the activation and disconnection of generators [2]. However, distributed generation contributes to strengthening the network and reducing losses. Thanks to the strengthened network structure, it is easier to overcome waveform distortions and voltage drops, which are among the power quality problems that may occur. To observe the effects of distributed generation on power systems, it is necessary to analyze power quality levels for situations before and after installation. An indicator is needed for this analysis.

Power quality indices are indicators that are used to quantify the degree of power quality deterioration that occurs in power systems for any reason [3]. Measuring the extent of power quality disturbances and their adverse effects on power systems can be performed using power quality indices. These indices are numerical representatives characterizing the nature of a power quality event on the basis of time or frequency information. There are studies in the literature evaluating the effects of distributed generation on power quality over indices. In 2009, appropriate probabilistic indices were used for distribution networks to evaluate power quality levels in the presence of distributed generation [4]. Bracale et al. [2] have taken into account the problem of assessing power quality levels in the presence of distributed generation. Therefore, they used probabilistic indices suitable for distribution networks. Nourollah and Moallem [5] aimed to obtain two global power quality

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indices to evaluate the power quality levels of several distribution regions according to the type of load and its location in the distribution system. Dash et al. [6] proposed the modified recursive Gaussian-Newton (MRGN) method for estimating power quality indices in distributed generation systems in both island mode and non-island mode states. In another study, they proposed a unified power quality index for the distribution network using a two-level analytical hierarchy process for possible, ideal, and real situations [7]. Alfieri et al. [8] developed new power quality indices to evaluate waveform distortions from 0 to 150 kHz in power systems where distributed generation is available. Elbasuony et al. [9] used the unified power quality index to evaluate the power quality in different distributed generation systems using the analytical hierarchy process. As a result of the study, it was observed that the suggested index makes it easier to evaluate the power quality. They also found that a hybrid system showed better power quality performance than other systems. Jasinski et al. [10] analyzed long-term power quality data using cluster analysis and a hybrid technique based on global power quality indices proposed by them. Moghaddam et al. [11] aimed to minimize losses and improve power quality indices by using the antlion optimization algorithm.

In this study, power quality indices were used to investigate the effects of distributed generation units on power quality. Various simulations were carried out on a real test system through Dig-Silent Power Factory, which is a power system analysis program. Power quality indices were computed for each case. Improvements in the voltage profile and THD were observed with the integration of distributed generation units into the system.

The remainder of this paper is structured as follows: the second section explains the power quality indices; the later section discusses the simulation study and results; and the conclusion section represents a summary of main findings of the study.

Methods

Power Quality Indices

Power quality addresses different aspects of the behavior of a power system. Its main function is to provide an uninterrupted voltage with sinus wave form at a fixed frequency to the end user.

Power quality variation indices are used to evaluate service quality. Variation indices are grouped under two headings. The first of these is single indices that address each power quality distortions we calculate using traditional indices. The second is global variation indices that simultaneously handle multiple power quality distortions. When evaluating a general power quality index for both types, the mentioned index presented with X, X_V and the power quality variation index (X_V), which allows to quantify the increase or decrease in power quality resulting from the integration of distributed generation units into the system, which is calculated as follows:

$$X\_V = \frac{X_O - X_N}{X_0} \quad (1)$$

X_N in equation 1 is the value of the single/global index X with the existence of distributed generation. X_O is the value of the single/global index X without distributed generation. All these indices can be calculated for each bus regionally as well as for the whole system under the name of system indices.

Single Variation Indices

Individual variation indices for all power quality disturbances can be obtained; however, in this study, only indices related to harmonic distortions and voltage changes will be evaluated.

Harmonic Variation Index

Equations for THD for voltage and current used commonly in the standards are given as follows:

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (2)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (3)$$

The harmonic variation index is an indicator that helps to compare the situation before and after the integration of the distributed generation unit into the system. Equation (4) is used to calculate the harmonic variation index for a region, that is, for a specific bus.

$$THD_{Vj} = \frac{THD_{Oj} - THD_{Nj}}{THD_{Oj}} 100 \quad (4)$$

where THD_{Vj} represents the THD variation index in the busbar j owing to the integration of a new distributed generation unit into the system, THD_{Oj} represents the total harmonic distortion value before integration of the distributed generation unit into the system, and THD_{Nj} represents the total harmonic distortion value after integration of the distributed generation unit into the system. If the value of this change index is positive, it indicates that there is an improvement in THD owing to distributed generation.

Voltage Variation

Calculation of voltage variation indices as well as harmonic variation index for a particular bus is very important in terms of in-

Main Points

- Power quality indices are used to evaluate the power quality in distribution networks.
- Distributed generation units are evaluated with power quality indices depending on their position in power systems.
- Distributed generation units are evaluated with power quality indices depending on their power.
- The cases of distributed generation sources being synchronous generators or wind farms are discussed.

creasing the quality performance of the power system. The regional voltage variation index is calculated as follows:

$$VDA_{Vj} = \frac{VDA_{Oj} - VDA_{Nj}}{VDA_{Oj}} 100 \quad [5]$$

where VDA_{Oj} represents the voltage variation value before integration of the distributed generation unit into the system and VDA_{Nj} represents voltage variation value after integration of the distributed generation unit into the system. If the VDA_{Vj} value is negative, it means that there is an improvement in the system in terms of voltage variation.

System Indices and System Variation Indices

The indices obtained as a result of calculating a specific power quality index for the whole system are called system indices. System indices are calculated using equation (6),

$$STHD = \frac{\sum_{k=1}^{M} w_k \, THD_k}{\sum_{k=1}^{M} w_k} \quad [6]$$

where w_k is the weight factor of the busbar k, M is the total number of busbars observed in the system, and THD_k refers to the total harmonic distortion index in the busbar k.

To determine the effect of distributed generation on system indices, system change indices calculated per equation (7) is used.

$$STHD_V = \frac{STHD_O - STHD_N}{STHD_O} 100 \quad [7]$$

A decrease in system indices indicates an improvement in power quality.

Global Variation Indices

Global indices allow general characterization of the voltage quality. The unified power quality index (UPQI), which is a global index, accurately represents the overall voltage quality in the presence of various disturbances. As in other indices, the change in UPQI should be calculated to have information about the effects of distributed generation on power quality. Equation (8) is used to calculate the variation in the UPQI.

$$UPQI_{Vj} = \frac{UPQI_{O,j} - UPQI_{N,j}}{UPQI_{O,j}} 100 \quad [8]$$

where $UPQI_{Vj}$ represents the UPQI variation index in the busbar j because of the integration of a new distributed generation unit into the system, $UPQI_{Oj}$ represents the unified power quality value before integration of the distributed generation unit into the system, and $UPQI_{Nj}$ represents the unified power quality value after integration of the distributed generation unit into the system. A positive UPQI variation index indicates an improvement in power quality in the power system.

Results

Simulation Study

The most common disturbances in power systems are voltage variation and harmonics. Voltage variation is defined as a decrease in voltage magnitude that occurs within the period specified by the standards. Harmonics can be defined as unwanted components of a distorted periodic waveform whose frequencies are integer multiples of the fundamental frequency [12]. As both power quality problems must be addressed, in this study, the aforementioned impairments were analyzed with the DigSilent Power Factory program, using power quality indices, on the basis of the presence or absence of distributed generation in the system.

In this study, the list of situations that were analyzed is given below:

- Calculation of THD variation indices for the situation where synchronous generators with different power levels are connected to the bus closest to the network and comparison of indices calculated at each power level.
- Calculation of THD change indices for the situation where synchronous generators with different power levels are connected to the bus, which is the furthest to the network and comparison of indices calculated at each power level.
- Calculation of voltage variation indices for synchronous generators with different power levels connected to the bus closest to the network and comparison of indices calculated at each power level.
- Calculation of voltage change indices for synchronous generators with different power levels connected to the bus, which is the furthest to the network and comparison of indices calculated at each power level.
- Calculation of system indices for synchronous generators with different power levels connected to the bus, which is the closest to the network and comparison of indices calculated at each power level.
- Calculation of system indices for synchronous generators with different power levels connected to the bus, which is the furthest to the network and comparison of indices calculated at each power level.

Test Setup

A feeder of Izmit 2 substation was selected for the implementation setup. The short circuit capacity of the system to which this feeder was connected was 418 MVA. The single line diagram of a 37 buses feeder is given in Figure 1 with its load values. The number of buses observed was 25 in total, 12 of which were load buses, and power factor for all loads was assumed to be 0.98 (inductive) [14].

The summary of busbars and loads are given in Table 1.

All mentioned loads are selected as harmonic sources, and the fifth harmonic value of the loads was 20%, the seventh harmonic value was 14.28%, the 11^{th} harmonic value was 9.09%, the 13^{th} harmonic value was 2.7%, and the 17^{th} harmonic value was 2.48%.

Simulation Results

Synchronous generators are considered as DGSs and modeled in the sample test system to improve the voltage profile and har-

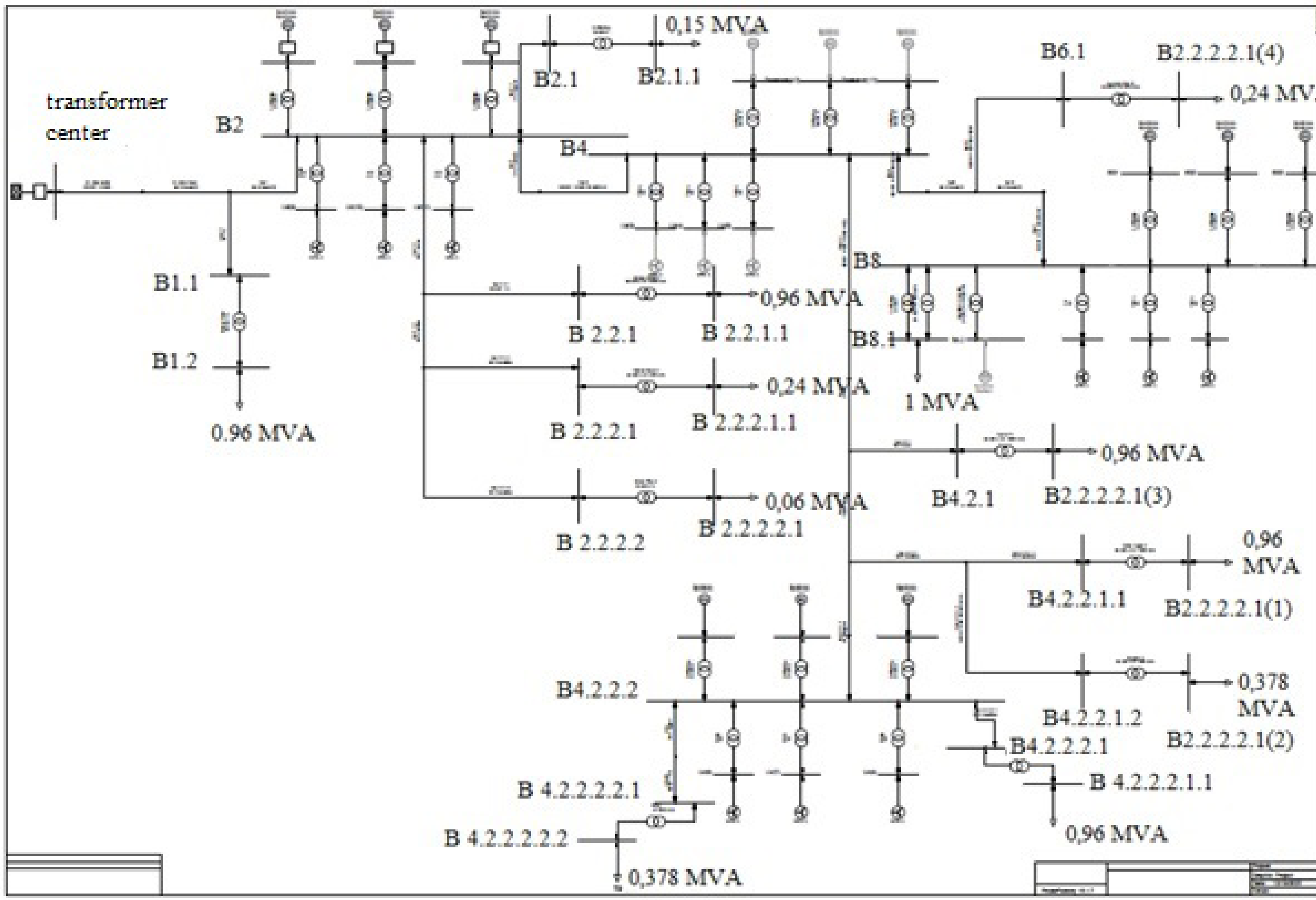

Figure 1. Single line scheme

Table 1. Summary of busbars

Busbar Name	Busbar Load (¹MVA)	Weighting Factor (w_j)
B2.1.1	0.15	0.020548
B2.2.1.1	0.96	0.131507
B2.2.2.1.1	0.24	0.032877
B1.2	0.96	0.131507
B2.2.2.2.1	0.06	0.008219
B2.2.2.2.1(1)	0.96	0.131507
B2.2.2.2.1(2)	0.378	0.051781
B2.2.2.2.1(3)	0.96	0.131507
B2.2.2.2.1(4)	0.24	0.032877
B4.2.2.2.1.1	0.96	0.131507
B4.2.2.2.2.2	0.378	0.051781
B8.1	1	0.136986
Total Load: 7.3 MVA		

monics. Simulation studies are carried out over the closest (B2) and the farthest (B4.2.2.2) busbars.

Three synchronous generators, each rated 1.9MVA were added to the test system. Analyses having one, two, and three synchronous generators were performed separately for THD and voltage change. THD change variation indices are compared in Figures 2 and 3, where DGSs are connected at the closest and farthest busbars, respectively.

As a result of the analysis, a decrease in THD values is observed with the integration of synchronous generators into the system. This decrease in THD values indicates an improvement in THD in the system. As can be seen, THD variation indices take positive values, which is a desired situation. In addition, the more rated power of DGSs, the more improvement for low THD. Another observation is that reduced harmonic levels are achieved as DGSs move away from the network.

The changes in voltage owing to the use of DGs connected at the closest and furthest busbars are given in Figures 4 and 5, respectively.

When analyzed in terms of voltage, an increase in voltage values with the integration of DGSs into system was observed. Because

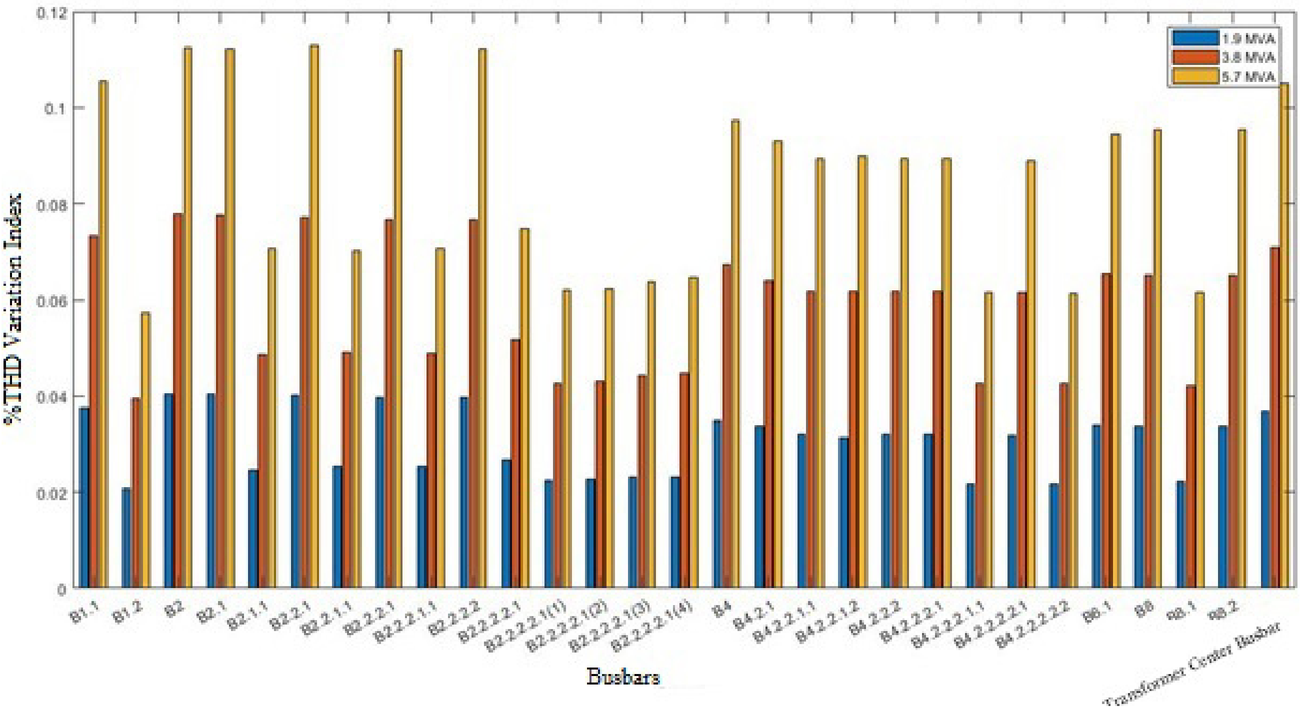

Figure 2. Total harmonic distortion variation index for the closest busbar (B2)

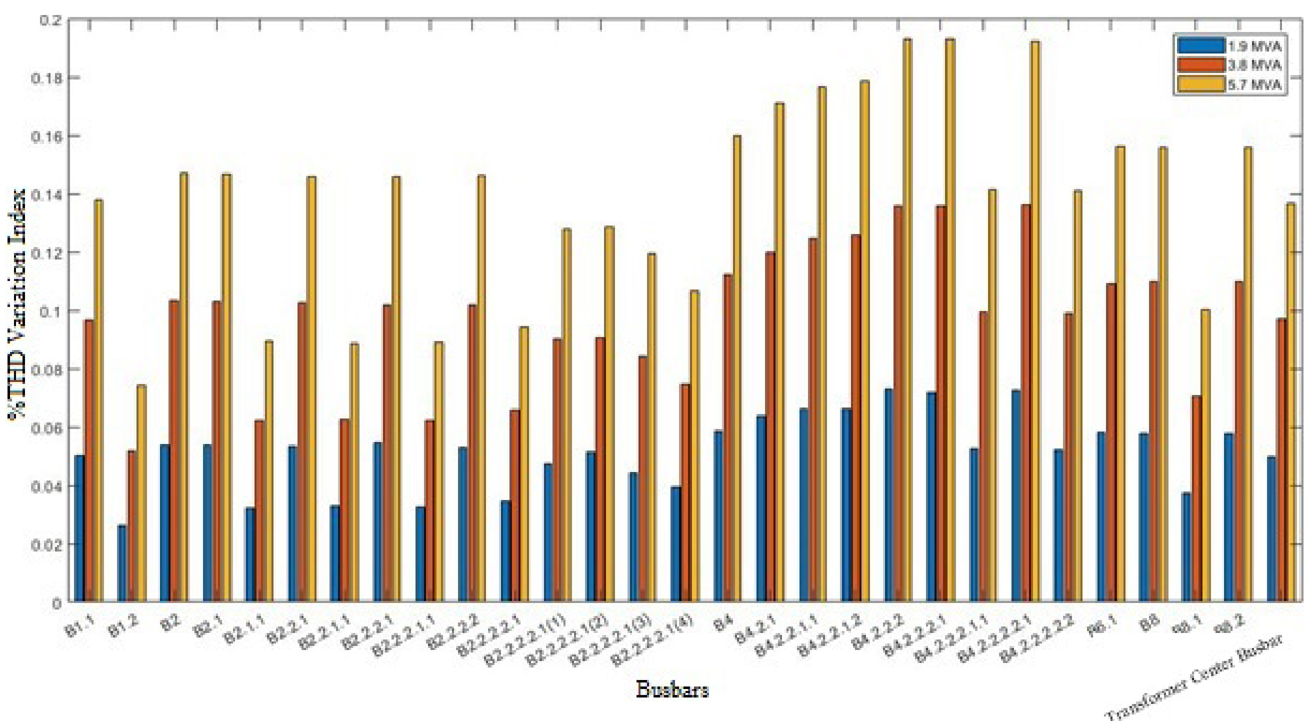

Figure 3. Total harmonic distortion variation index for the furthest busbar (B4.2.2.2)

of the increase in the voltage values, the voltage variation indices take negative values as should be. This indicates that the test system is enhanced in terms of power quality.

Knowing the general status of the system is important in terms of having information about the distribution system [13]. Therefore, the system indices for synchronous generators with different

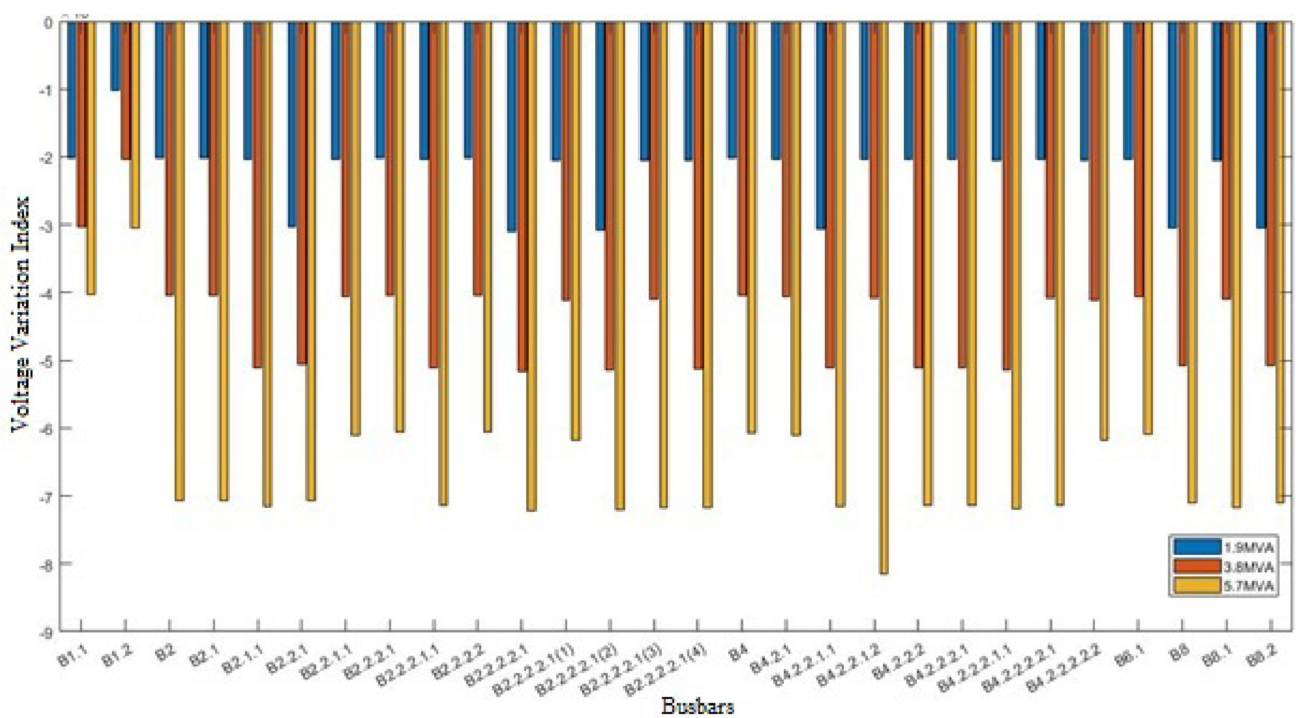

Figure 4. Voltage variation index for the closest busbar (B2)

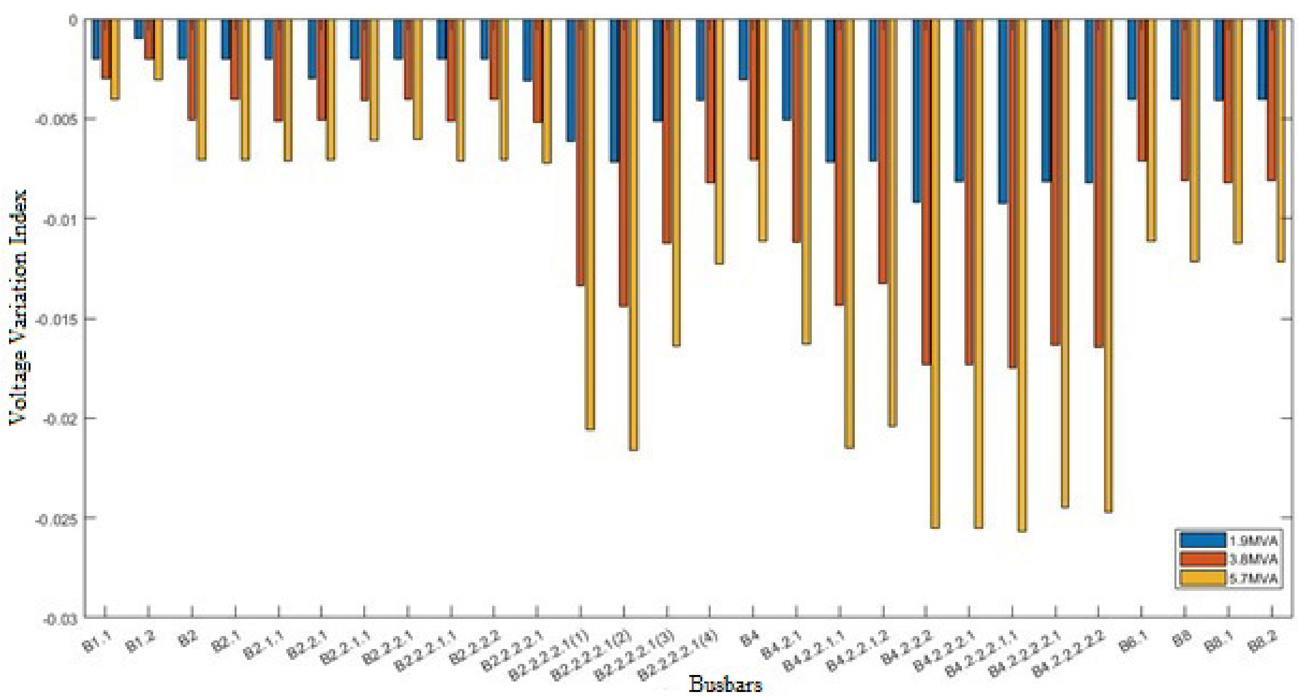

Figure 5. Voltage variation index for the furthest busbar (B4.2.2.2)

power levels connected to the buses, which are the closest and furthest to the network are calculated. Comparison results are given in Table 2.

It was observed that the values of the system indices for THD decreased as the power increased. According to these results, it was determined that there was an improvement in power quality with

Table 2. Comparison of system indices for closest and furthest buses

Power Levels	Closest Bus (B2)	Furthest Bus (B4.2.2.2)
1.9 MVA	0.133861	0.130658
3.8 MVA	0.130994	0.125273
5.7 MVA	0.128344	0.120333

MVA: Megavolt Ampere

increasing power. Again, when we make a comparison in terms of the closest and the furthest bus, it can be said that there is an improvement in terms of system indices as we move away from the network.

When all results are evaluated together, the obtained results are specific to the system and the scenario (system topology). At this point, the difference in the distribution of the loads in the system rather than the different sources or the distance situation are effective in the results obtained.

Discussion

Distributed generation is a reality today and may have positive and negative impact on a power system. In this study, its positive impact in terms of power quality has been investigated. For this purpose, the power rating and the position of distributed generation has been varied, and the performance of the system has been measured with power quality indices related to voltage harmonics and voltage profile. A feeder belonging to Izmit 2 Transformer Station had been used to carry out analyses. The results showed that with the integration of distributed generation units into the system, improvements were demonstrated in THD and voltage profile as the power rating of DGSs increased, and their location was further away from the network.

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RESEARCH ARTICLE

Delay-dependent Stability Analysis Considering Dynamic Demand Response and Electric Vehicle Aggregator Integration in Two-Area Load Frequency Control Systems

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ABSTRACT

In this study, we determined the stability delay margins in a two-area load frequency control (LFC) system enhanced by electric vehicles (EVs) and demand response (DR) control. EVs based energy storage devices and responsive loads for DR control are becoming promising tools for electric power systems facing challenges in frequency stabilization. However, an open communication network used to send and receive the control signals can cause inevitable time delays, which could lead to undesired oscillations in the system frequency. Therefore, it is essential to obtain stability delay margins in the two-area LFC system with EVs and DR control for a stable operation. By constituting the enhanced LFC system model in Matlab/Simulink environment, we determined stability delay margins for randomly selected proportional-integral controller gains and various participation ratios of DR control and EVs along with the battery's state of charge consideration influencing gains of EVs.

Keywords: Demand response, electric vehicles, load frequency control, stability delay margin

Introduction

In this study, we aimed to obtain stability delay margins considering the integrations of electric vehicles (EVs) and dynamic demand response (DR) control into two-area load frequency control (LFC) system with constant communication delays. Interconnected power systems need a stable frequency profile to maintain the system reliability and security during disturbance events. Therefore, LFC mechanisms are employed to mitigate system frequency fluctuations and to maintain power exchange among control areas at the scheduled value when sudden changes may occur between load demand and generation [1]. Recently, the contribution of renewable energy (RE) sources including photovoltaic and wind power systems in power generation of the smart grids has considerably increased. Similarly, frequency regulation is becoming a difficult task because of highly penetration, variable generation, high costs, and low efficiency of RE sources [2]. To solve the increasing frequency control issues and to keep power grid's stability, EVs batteries as a power generation unit and DR control methodologies have become a promising tool for conventional LFC systems.

DR control, which was first introduced by [3], is based on real-time smart active participation of controllable loads for proper balancing between generation and peak load demand. Some examples of these controllable loads contain battery charging/discharging and thermostatically controlled loads like fridges, freezers, HVAC, electric water heaters, and vehicle to grid services that have fast response. DR control mechanism has proven faster and more reliable than the traditional methods in maintaining the balance between demand and generation. DR programs are achieved by the changes in the electricity utilizing load control applications from their regular consumption patterns and are broadly categorized as incentive-based (dispatchable) programs and time-based (non-dispatchable) programs [4, 5]. In the modern smart grid era, DR offers diverse services. It can be used to financially incentivize utility companies as well as customers [6], neutralize the impacts of intermittency of RE sources [7], provide ancillary services and mitigate the voltage and frequency fluctuations [8]; and it has various other uses such as transmission expansion planning [9] and improved transformer utilization [10]. Therefore, the DR control is a useful compensation for conventional power system frequency regulation approaches because of its fast response, flexibility, and economic efficiency. Most of the studies on DR control assume that flexible loads could be instantly controlled without communication time delays. However, a centralized control scheme is re-

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quired to consider the communication time delay observed in the DR control loop. Some studies report that the control loop has communication latencies, including frequency detection error, frequency measurement errors, data calculation delay, the terminal controller delay, data uplink delay, and control downlink delay [11, 12]. Many researchers have discussed the effect of time delays on the LFC system with DR control. The effect of time delay on the DR control loop using padé approximation approach for a single-area LFC system with DR control was investigated in [13]. In [14], the DR control loop with communication time delay was integrated to a two-area thermal LFC system, and the controller parameters of LFC and DR loops were optimized using particle swarm optimization technique to guarantee minimum frequency deviation profile. To decrease frequency detection error and the effect of communication delays, in [11] they have developed a hybrid control approach as a combination of centralized and distributed control methods used to control the flexible loads. In [12], they have proposed active disturbance rejection control to increase the robustness of frequency against the load disturbances and uncertainties in system parameters and designed an adaptive delay compensator to decrease the impact of communication delays for single-area LFC system with DR control loop.

Recently, the integration of EVs into frequency regulation service because of their quick responses has drawn attention to LFC systems. With the help of EVs, frequency deviations could be reduced and hence system frequency response improved as they could be operated as loads or generators [15, 16]. The practical participation of EVs in frequency regulation market is regulated by an entity known as EVs aggregators, which are employed to accumulate and control a large fleet of EVs to meet the frequency regulation criteria [17, 18]. Furthermore, the main functions of EVs aggregators are to gather information about the charging status of participating EVs, their energy capacities and electrical power availability and transmit it to the controller. The aggregators rearrange the control signals to disperse the participating EVs for the adjustment of their power output by employing automatic generation control. To transmit control commands to EVs for automatic generation control, the EVs aggregator is equipped with a dedicated or an open communication network. The use of communication networks for EVs aggregators leads to communication time delays, which adversely affect the system dynamic performance and may even cause instability [19-21]. The response time to the regulation command by an Independent System Operator (ISO) is imperative in frequency regulation service. Normally, ISO transmits commands every 2 to 6 seconds to the aggregator [22]. To respond to regulation signals, ISOs usually have their own specific protocols for allowing maximum communication delay; for example, ISO of California allows a communication time delay limit of 4 seconds between EVs and the aggregator [23]. Therefore, it is important to determine the stability delay margins known as tolerable upper bound limit of time delays. To compute delay margins, the existing literature has mainly proposed the numerous approaches categorized as frequency domain direct methods and time-domain indirect approaches. Rekasius substitution [24], direct method [25], delay space re-scaling approach [26], and frequency sweeping test [21] are some of the frequency domain direct methods. These methods can be applied to systems having only commensurate time delays, and they are able to compute all critical purely imaginary roots of the characteristic equation and delay margin values that will be marginally stable of system. The qualitative methods are successfully implemented to calculate the stability delay margins of LFC systems with/without EVs [21, 25, 27], micro-grid LFC systems [24], and to estimate stability delay margins of DC micro-grids [26]. A detailed literature study on the methods for delay margin estimation of linear time-invariant continuous-time systems is reviewed in a survey presented in [28]. Time-domain indirect approaches that can be applied to systems having constant and time varying delays is based on Lyapunov stability theory and linear matrix inequalities techniques used to determine the delay margins [19, 29]. These methods are mainly implemented to determine the stability delay margins of LFC systems with/without EVs [19, 29]. In addition to time delay issues of LFC system with EVs, dynamics of EVs could be affected by uncertainties owing to the large number of EVs. Especially, EVs according to battery's state of charge (SOC), which is an indication of EVs charging/discharging states, could be operated as a generation unit and load. EVs gains are usually set as a constant value to simplify the aggregated EVs model. However, EVs gain must be considered to be time varying owing to uncertainties in the EVs fleet [30, 31]. Therefore, the impact of EVs model parameters on the stability delay margins must be examined.

We reviewed existing literature to investigate the delay-dependent stability analysis of the time-delayed LFC systems, including DR control or EVs aggregator. The integration of the methodologies into power system and the observed time delays considerably increase the complexity and degree of the LFC systems. Therefore, the impact of combined DR control and EVs on the delay-dependent stability of the LFC systems must be considered. Accordingly, this work implements time-domain simulations in Matlab/Simulink environment [32] for estimation of the delay margin values considering different participation factors of DR control and EVs model along with its parameters. The major contributions of this study could be summarized as following:

- Two-area LFC system model having time delays in both EVs aggregator side and DR control loop is first constituted in Matlab/Simulink. The system is called as two-area LFC-DR-EVs system.
- Necessary frequency control efforts of EVs aggregator and DR control on the frequency regulation service are accom-

Main Points

- Delay-dependent stability analysis of time-delayed two-area load frequency control (LFC) system including electric vehicles (EVs) and dynamic demand response (DR).
- The investigation of effect of the EVs parameters on the system stability margin for time-delayed two-area LFC system including EVs and DR control.
- The effect of the participation factors of EVs and DR control on the determined stability margins.

plished by their participation ratios. To examine the effect of combined DR control and EVs on the LFC system stability, delay margin results are obtained by time-domain simulations for different participation factors of DR control and EVs aggregator along with selected proportional-integral (PI) controller gains.

- To evaluate the effect of the EVs parameters on the system stability margin, delay margins of the LFC-DR-EVs system under the variations of EVs parameters are determined by time-domain simulations.

Time-Delayed Two-Area LFC System Model with DR Control and EVs Aggregator

The block diagram of the two-area LFC-DR-EVs system is shown in figure 1. It should be noted that the conventional LFC system is modified by adding DR control loop and EVs aggregator, represented by dashed lines. A large number of EVs is plugged into the power grid to provide a quick balance between demand and generation. The aggregator is responsible for coordination of communication between control center and EVs to send/receive the information regarding the charging/discharging states of each EV integrated into the grid. The dynamic model of the *i*-th EV in the EVs aggregator can be presented by the following first-order transfer function [16, 30]:

$$G_{EV,i}(s) = \frac{K_{EV,i}}{1 + sT_{EV,i}} \quad (1)$$

where, $T_{EV,\,i}$ and $K_{EV,\,i}$ $(i=1,2)$ represent the time constant and the gain of the *i*-th area EV battery system, respectively. The time constant ($T_{EV,\,i}$) and gain ($K_{EV,\,i}$) are two important parameters of EVs. The time constants $T_{EV,\,i}$ are assumed to be equal in an average sense. EVs are connected with the grid through an inverter to control the active and reactive power. Therefore, the time constant ($T_{EV,\,i}$) could be varied depending on circuit parameters designed for the connection between EV charger and grid. This information is taken from EV charger manufacturers [16]. Although EVs gain ($K_{EV,\,i}$) is assumed to be set to a constant value, the gain is a time-varying parameter according to SOC consideration. The decision of EVs batteries' charging/discharging and their output power deviations are determined by EVs battery's SOC, which influences the EVs gains and manages the participation of EVs. Therefore, EVs gain is given as follows:

$$K_{EV,i} = \bar{K}_{EV,i} - \bar{K}_{EV,i}\, g(t) \quad (2)$$

where, $\bar{K}_{EV,\,i} = 1$ and $g(t)$ is a function used to evaluate SOC status and is expressed as $0 \leq g(t) \leq 1$.

This means that $K_{EV,\,i}$ will be a value in the range of [0,1] [30, 31]. Therefore, the uncertainties and variations of EVs parameters must be considered to obtain the stability delay margins, and the effect of these parameters on the delay margins must be investigated.

In figure 1, a PI controller in each LFC area is adopted for both secondary control and DR control loops.

$$G_{ci}(s) = K_{Pi} + \frac{K_{Ii}}{s} \quad (3)$$

where, K_{pi} and K_{Ii} are the proportional and integral controller gains, respectively.

All PI controllers employed in the two-area LFC system are assumed to be identical to easily find the delay margin values. Moreover, Δf_i, ΔP_{Li}, ΔP_{gi}, ΔP_{mi}, ΔX_{gi} and $\Delta P_{EV,\,i}$ indicate the deviation of frequency, load disturbance, power output of generator, mechanical power output, valve position, and EVs aggregator power output of the *i*-th control area $(i = 1, 2)$, respectively. In addition, D_i, M_i, R_i, β_i, F_{pi}, T_{ci}, T_{ri}, and T_{gi}, are the damping coefficient, generator inertia constant, speed drop, frequency bias factor, total turbine power's fraction, time constants of the turbine, reheat and governor, respectively. Furthermore, T_{12}, in figure 1 denote the tie-line synchronization coefficient responsible for the schedule power exchange between two control areas.

With the integration of the DR control and EVs aggregators into the two-area LFC system, the contributions of EVs aggregator, DR control and classic generation unit to the frequency regulation service are accomplished by the participation factors given as following [13,19]:

$$\begin{aligned} \Delta P_{s,i}(s) &= \alpha_0 \Omega \\ \Delta P_{EV,i}(s) &= \alpha_1 \Omega \\ \Delta P_{DR,i}(s) &= \alpha_2 \Omega \end{aligned} \quad (4)$$

where, a_0, a_1, a_2, and Ω represent the participation ratios of classic generation units, EVs and DR control for each LFC area, and the required the controlling effort, respectively.

The algebraic sum of the participation ratios is $a_0 + a_1 + a_2 = 1$. In addition, total amount of communication time delays observed in both EVs aggregators side and DR control loop is τ_1 and τ_2, respectively. It should be noted that the EVs aggregators and DR control loop added to each control area have exponential transfer functions described as $e^{-s\tau_1}$ and $e^{-s\tau_2}$. In this study, the delays in each control area are assumed to be equal $e^{-s\tau_1} = e^{-s\tau_2} = e^{-s\tau}$.

Delay Margin Definition

Stability analysis of LFC systems with time delay is generally categorized into delay-independent or delay-dependent analysis. Depending on system parameters, the two types of the stability situations can be explained as follows [25]:

i) *Delay-independent stability*: The system is said to be delay-independent stable if the stability of LFC system could be kept for all positive and finite values of the delay, $\tau \in [0,\infty]$.

ii) *Delay-dependent stability*: The system is said to be delay-dependent stable if the stability of LFC system could be kept for some values of delays belonging in the delay interval, $\tau \in [0,\tau^*]$, and is unstable for other values of delay $\tau \geq \tau^*$.

Delay-dependent stability case can be illustrated by figure 2. The LFC system is asymptotically stable when the real parts of all

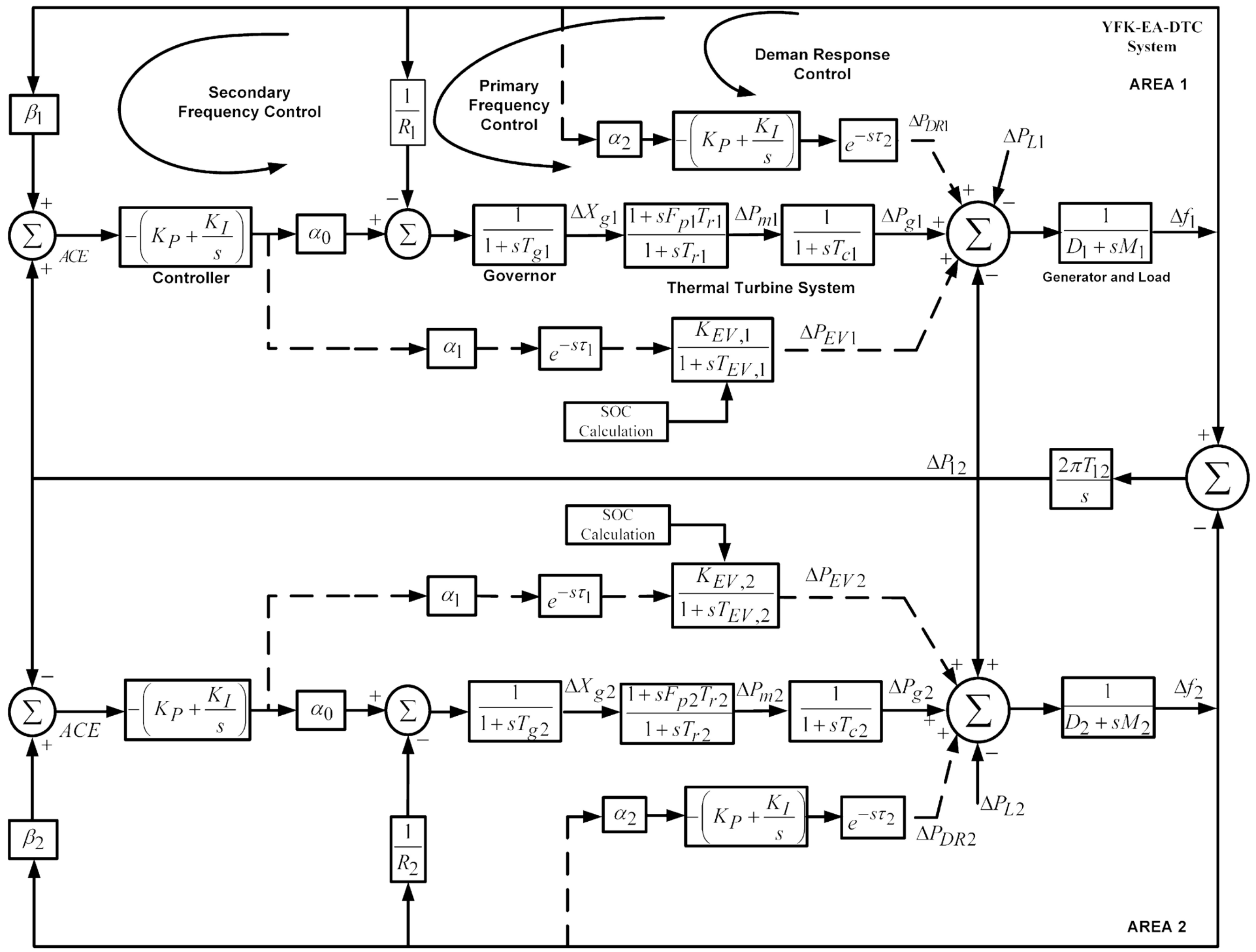

Figure 1. The time-delayed two-area LFC system model with EVs aggregators and DR control

roots of LFC system are negative. Accordingly, it is assumed that all eigenvalues of the LFC system for $\tau = 0$ are first located in left half of complex plane, and thus the LFC system at $\tau = 0$ satisfies the asymptotic stability condition. With increase of time delay ($\tau > 0$), some of eigenvalues could move to the right half plane as shown from figure 2. For $0 < \tau < \tau^*$ ($\tau = \tau^* - \Delta\tau$, the LFC system is stable as complex eigenvalues are close to the imaginary axis as shown in figure 2. Next, it should be noted that the LFC system for $\tau = \tau^*$ has critical roots on the imaginary axis. Therefore, τ^* is defined as allowable delay bound or stability delay margin such that the LFC system is marginally stable owing to the critical roots. For a time delay greater than the allowable delay ($\tau = \tau^* + \Delta\tau$), the LFC system has the pair of the complex eigenvalues in the right half plane. Therefore, the LFC system will be unstable for a finite time delay ($\tau^* < \tau$). In this study, we aimed to determine the delay margin values of the two-area LFC system for different participation factors of EVs aggregator and DR control and variable parameters of EVs aggregator.

Results

This section presents delay margin results of the two-area LFC system, including EVs aggregators and DR control whose control loops have the communication time delay. The LFC system model is constituted in Matlab/Simulink environment. First, the effect of participation factors of DR control and EVs aggregator on the stability delay margins is broadly investigated by time-domain simulations in Matlab/Simulink environment [32]. Considering the variations of EVs aggregator parameters (time constant and gain), stability delay margins of the LFC system are then obtained. The two-area LFC-DR-EVs system parameters are given as following [19]:

$$M_i = 8.8s,\ D_i = 1,\ F_{pi} = 1/6,\ R_i = 1/11\ pu,\ \beta_i = 21\ pu/Hz,\ T_{gi} = 0.2\ s,\ T_{ci} = 0.3\ s,\ T_{ri} = 12\ s,\ T_{12} = 0.1\ pu,\ K_{EV,i} = 1,\ T_{EV,i} = 0.1\ s \text{ for } i = 1,2 \quad [5]$$

Impact of the Participation Factors of DR Control and EVs Aggregators

The prime objective of this section is to obtain the stability delay

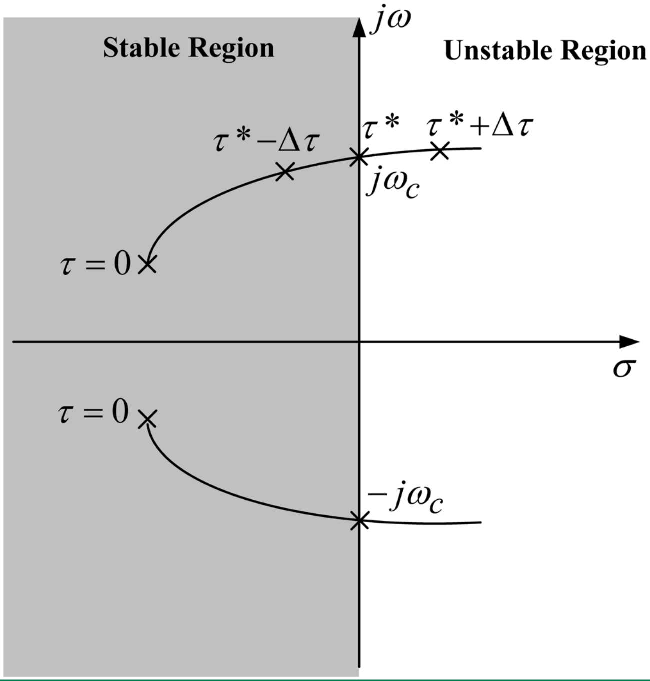

Figure 2. Illustration of the roots movement with respect to the time delay

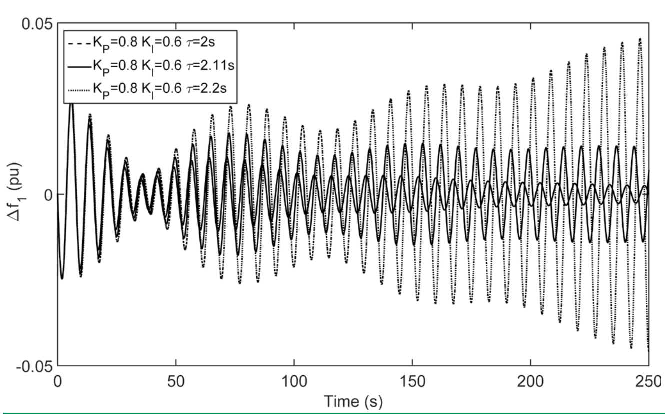

Figure 3. The frequency responses for different time delay values

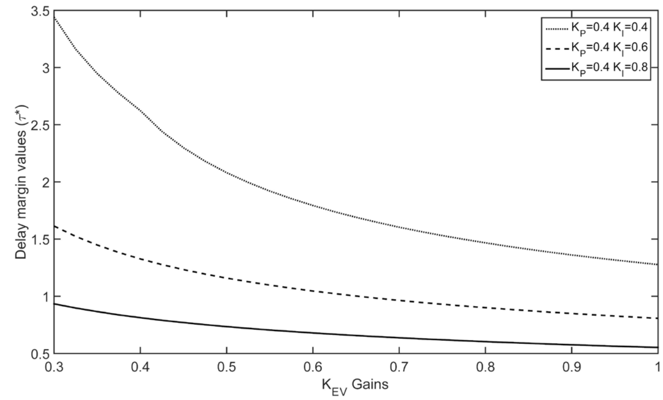

Figure 4. The effect of EVs gains on delay margins for three different PI controller gains

Table 1. Delay margins results for $a_0 = 0.8$, $a_1 = 0.1$, and $a_2 = 0.1$

$\tau^*(s)$			K_I		
K_P	0.2	0.4	0.6	0.8	1.0
0.2	∞	1.76	0.73	0.27	0.02
0.4	∞	2.85	1.32	0.74	0.41
0.6	∞	4.05	1.78	1.12	0.74
0.8	∞	∞	2.11	1.40	1.0
1.0	∞	∞	2.32	1.60	1.20

Table 2. Delay margins results for $a_0 = 0.6$, $a_1 = 0.3$, and $a_2 = 0.1$

$\tau^*(s)$			K_I		
K_P	0.2	0.4	0.6	0.8	1.0
0.2	2.38	0.94	0.51	0.36	0.19
0.4	2.38	1.28	0.81	0.56	0.40
0.6	2.08	1.39	0.98	0.73	0.56
0.8	1.77	1.35	1.05	0.83	0.67
1.0	1.51	1.24	1.03	0.86	0.73

margins in two-area LFC-DR-EVs system for a given set of PI controller parameters and participation ratios of EVs aggregator and DR control. For each LFC area, sharing factors of EVs aggregator and DR control to participate in frequency regulation service are selected as ($a_1 = 0.1$) and ($a_2 = 0.1$), respectively. Thus, the conventional generation unit meets the high ratio of the power sharing ($a_0 = 0.8$). The contribution to frequency regulation services by conventional generation unit (80%), EVs aggregator (10%), and DR control (10%) seems very practical. Delay margin values are obtained by time-domain simulation for given participation factors and PI controller gains and those values are tabulated in Table 1. The LFC-DR-EVs system is delay-independent stable for PI controller gains corresponding to the positions symbolized by "∞" as indicated in Table 1. To investigate the effect of EVs aggregator on the stability delay margins, the sharing ratio of EVs aggregator is increased from 10% ($a_1 = 0.1$) to 30% ($a_1 = 0.3$), and participation ratios of DR control and conventional generation unit are set to 10% ($a_2 = 0.1$) and 60% ($a_0 = 0.6$) , respectively. The delay margin results corresponding to the case are given in Table 2. From Table 2, it can be seen that the delay margin values for all PI controller gains decrease when Table 2 is compared with Table 1. The increase of the EVs aggregator participation on the frequency regulation decrease the stability margin. Another aim was to examine the effect of DR control participations on the stability delay margins. To achieve this, the sharing ratio of DR control is increased from 10% ($a_1 = 0.1$) to 30% ($a_1 = 0.3$), and participation ratios of EVs aggregator and conventional generation unit are considered

Table 3. Delay margins results for $a_0 = 0.6$, $a_1 = 0.1$, and $a_2 = 0.3$

$\tau^*(s)$			K_I		
K_P	0.2	0.4	0.6	0.8	1.0
0.2	∞	1.99	0.95	0.49	0.24
0.4	∞	2.84	1.43	0.87	0.56
0.6	∞	3.49	1.79	1.18	0.83
0.8	∞	3.95	2.01	1.41	1.05
1.0	∞	4.22	2.12	1.56	1.21

as 10% ($a_2 = 0.1$) and 60% ($a_0 = 0.6$), respectively. The delay margin results corresponding to the case are shown in Table 3. Table 3 indicates that the delay margin values for almost all PI controller gains increase when Table 3 is compared with Table 1. The increase of the DR control participation reveals that stability margin of the LFC system is greatly improved. Moreover, the effect of the integral controller gains on the delay margin values is investigated. Stability delay margins decrease as the integral controller parameter (K_I) increases for a fixed K_P controller parameter as shown in Tables 1-3, indicating a less stable LFC-DR-EV system.

The secondary objective of this section is to verify the delay margin results presented in Tables 1-3. For the validation, the frequency responses of the LFC-DR-EVs system is simulated under load disturbance of $\Delta P_{L1} = 0.2\ pu$ ($\Delta P_{L2} = 0$) at $t = 0$. PI controller gains, and the participation factors are selected as ($K_P = 0.8$, $K_I = 0.6$), $a_0 = 0.8$, $a_1 = 0.1$, and $a_2 = 0.1$, respectively. Delay margin value corresponding to the selected parameters is determined as $\tau^* = 2.110s$ in Table 1 and figure 3. illustrates the frequency deviations of the LFC system for selected time delay values ($\tau = 2.030s < \tau^* = 2.110s$ and $\tau^* = 2.110s < \tau = 2.190s$ around the delay margin ($\tau^* = 2.110s$). The LFC system is stable at $\tau = 2.030s$ because of decreasing oscillations of system frequency, whereas at $\tau^* = 2.110s$, the LFC system is marginally stable owing to sustained oscillations of system frequency. Finally, the LFC system exhibits unstable behavior at $\tau = 2.190s$ owing to growing oscillations of system frequency.

Impact of EVs Aggregator Parameters

EVs aggregator has two important parameters referred to as time constant (T_{EV}) and gain (K_{EV}). According to [2], K_{EV} depending upon the SOC of EVs could change in the interval of (0.1). Referring to the circuit specifications obtained from EVs charger manufacturer, T_{EV} could set in values of 35 ms, 50 ms, and 100 ms [16]. Therefore, it is significant to analyze the stability margins considering variations in EVs parameters. Figure 4 gives the stability delay margin values for $K_{EV} \in [0.3,1]$ and PI controller gains chosen as ($K_p = 0.4$, $K_I = 0.4$), ($K_p = 0.4$, $K_I = 0.6$) and ($K_p = 0.4$, $K_I = 0.8$) when the participation ratios of conventional generation unit, EVs aggregator, and DR control are specified as $a_0 = 0.6$, $a_1 = 0.3$, and $a_2 = 0.1$, respectively. Figure 4 clearly indicates that the delay margin results decrease as the K_{EV} parameter increases. The increase of the K_{EV} results in the decrease of the LFC system stability margin. Finally, Table 4 tabulates the stability delay margins for $T_{EV} = 35ms$. It is seen from Table 4 that the decrease of T_{EV} parameter results in the increase of the stability margin of the LFC-DR-EVs system when Table 4 is compared with Table 1. Therefore, these parameters in terms of stability delay margins should be considered to investigate the system stability margin.

Discussion

This study demonstrated the stability delay margins in a two-area LFC-DR-EVs system for different participation ratios of generation units and selected PI controller gains along with variations in the EVs parameters. The effect of DR control and EVs on the stability delay margin was examined. The DR control participation improves the system stability margin, whereas the increasing participation of EVs leads to a decrease in stability margins of the LFC system. The simulation studies have clearly proved the stable, marginally stable, and unstable behaviors of the system frequency responses for the selected time delay values around and on the delay margin value. Moreover, stability delay margins considering the variations of gain parameter of EVs are obtained. Higher values of the EVs gains lead to decrease delay margin values. Another analysis was performed to investigate the time constant of EVs on the delay margins. Similar to the EVs gain case, the increase in EVs time constant decreases the delay margins.

Future studies should focus on the determination of stability delay margins for the two-area LFC-DR-EVs system with multiple incommensurate time delays using theoretical delay margin computation methods.

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RESEARCH ARTICLE

Determination of Proper Angle Settings in Resistance Grounded Distribution Systems for Directional Earth Fault Relays

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ABSTRACT

The intensive use of the underground cables in distribution systems, eventually, results in the total phase-ground capacity of the system to increase. High magnitude of capacitive currents causes capacitive current based sympathetic tripping problem to occur frequently at the distribution system. Directional protection relays may be used to eliminate the sympathetic tripping problem and protect the system selectively. However, it should be known that selective operation of directional relays entirely depends on suitable angle settings. Non-properly angle settings may cause mal operation of directional protection relays. Thus, angle setting of directional protection relays is utilised considering cable cross section area, cable length, parallel feeders number and neutral earthing resistance in this study. The efficiency of the selected angle settings methodology has been confirmed over a field-case distribution system.

Keywords: Cable, earth fault, directional protection

Introduction

Distribution systems (DS) are subject to various type of faults during operation stages. The most common type of faults is single line to earth faults (SLEF) that makes approximately 85% of total faults of the system [1]. Faults can be quite hazardous for supply security, safety and reliability. There is no solution for prevent fault occurrence or global protection methods which covers all DS types. Over-current protection relays constitute the brain of the system since the over-current protection is primary protection strategy in distribution networks also back-up protection for distance protection in transmission systems [2]. However, traditional non-directional relays may have not provided selectivity. Additional directionality is needed in most cases.

With the increase in energy demand and urbanization, the usage of underground cables instead of overhead lines has become widespread. Especially in metropolitan cities, there is a huge density of cable network employment in DSs. This situation causes the total phase to earth capacitance of DSs to increase. Under normal operating conditions, underground cable length has favourable effects on voltage drop by causing capacitive loading. However, it plays a decisive role on selectivity under fault conditions. Over-currents and / or over-voltages may be observed during SLEFs. However, due to the extensive usage of underground cables in the DSs, high magnitude of earth fault (EF) can also be seen in the protection zones where the fault does not occur in. This event may cause some kind of sympathetic (false, unnecessary, unwanted) tripping and cause problems in energy supply security and financial losses for DS operators [3-4]. Main reasons for false sympathetic trips; mal operation of circuit breakers, voltage unbalance, use of intense distributed generation, starting currents of motors, mutual coupling effect of cables in the same tranches and capacitive currents of cables [6-7]. Studies in which these reasons are analysed separately can be found in the literature [6]. In this study, the capacitive current of underground cables has been focused on giving particular emphasis for correct angle settings.

Non-directional overcurrent relays as a habit that comes from the periods of heavy use of overhead lines, in the case of heavily undergrounded/cabled systems, non-directional relays fail to provide required selectivity. Directional earth fault (DEF) relays become widespread provide selectivity in DSs. Conventional DEF relays need the angle of the voltage and therefore a voltage transformer in order to determine the direction of the fault [8]. This situation makes the implementation of DEF protection practice more costly when compared with conventional over- current protection system. It is known that only current-based protection algorithms have also been developed, recently [9-10]. However, whichever al-

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gorithm is used, determining the appropriate angle setting and implementing it to DEF relay are a matter of expertise.

In this study, SLEFs in different scenarios are analysed by taking into account the variable parameters of DSs such as; neutral earthing resistance, feeder length, cable cross-section area, number of parallel feeders. Magnitudes and angles of the faulty and healthy feeder currents are presented as contour graphs for each SLEF scenario. Thus, it is aimed to develop a tool where the DS operator can view the system from a wide range and obtain information about the protection settings that they can be applied in case of possible EFs.

Main contribution of this paper is utilisation of contour curves for appropriate DEF relay settings for both; pick-up and angle. In order to show the validity of usage of contour curves for selective protection settings, an exemplary substation with four feeders is modelled and various SLEFs are analysed. It has been observed that selective protection settings can be determined with greater accuracy by using developed contour curves.

This paper designed as follows; Section II summarises sympathetic tripping problem due to capacitive currents. Implementation of DEF protection settings are also detailed in this section. Section III introduces a methodology for DEF relay settings based on contour graphs. Section IV present application of proposed methodology and its selective protection performance. Section V draws the conclusions.

Sympathetic Trip in DS Based on Capacitive Currents

In addition to being the simplest layout, radial DS is the most widely used configuration in Turkey and in many other countries of the world. Power flow is unidirectional from the source through the load. Thanks to its unidirectionality, radial DSs have been protected selectively against EFs using nondirectional overcurrent relays for a long time [11]. The employment of distributed generation to DSs [12], extensive usage of underground cables instead of overhead lines [6] and increase in large-power motors fed by the system made it necessary to revise the protection philosophy even in radial DSs.

The three-phase equivalent circuit of a sample radial DS with two separate feeders is shown in Figure 1. To protect DSs against earth faults, two EF relays are located at the feeders-heads. Relay R_1 and relay R_2 are placed in faulty and healthy feeders sections, respectively. To maintain selectivity only relay R_1 must see the fault referring in Figure 1, in any case relay R_2 should remain intact. In some cases, in addition to the first feeder, the relay on the second feeder can detect the fault and generate a false tripping signal.

Main Points

- Detailed examination of the Sympathetic tripping problem in highly underground cabled distribution networks.
- Novel curve-based relay setting proposed in this article depending on cable cross-section area, cable length, number of parallel feeders, and neutral earthing resistance.
- Proposed curve-based relay setting method applied 62 node distribution networks and selective earth fault protection ensured for all possible fault location.

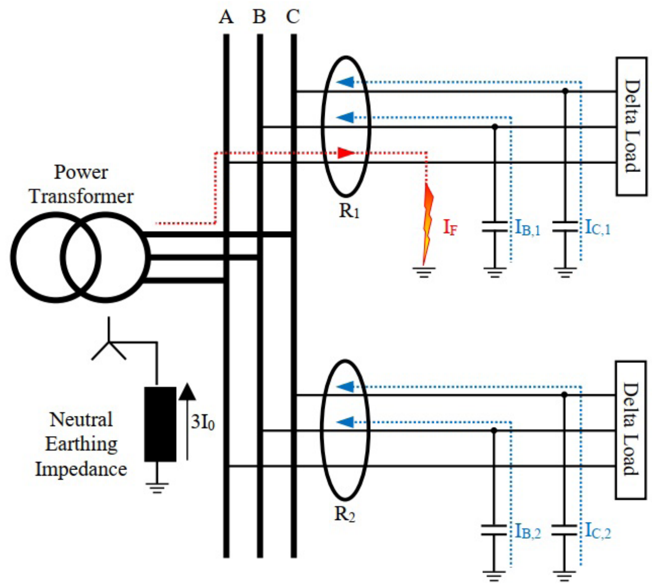

Figure 1. Current circulating in radial distribution network under SLEF condition

In a balanced system, the vector sum of the phase currents should be zero. Thus, zero sequence current (I_0) is measured by EF relays to detect SLEFs. If measured zero sequence current value is higher than the pick-up value of the relay setting, the relay generates operating signal. Magnitude of the fault current $\overline{I}_F$ calculated by Equation (1). Where $3\overline{I}_0$ is the neutral current, $I_{C,n}$ and $I_{B,n}$ represents capacitive current of nth feeder. Magnitude of zero sequence current seen by the first EF relay calculated by Equation (2). Capacitive currents flow back and forth through current transformers in the faulty feeder. Thus, vectoral sum of these currents is also zero. Hence, Equation 3 is obtained. Similarly, the zero sequence current seen by the relay R_2 given in Equation 4.

$$\overline{I}_F = 3\overline{I}_0 + \overline{I}_{B,1} + \overline{I}_{B,2} + \overline{I}_{C,1} + \overline{I}_{C,2} \quad (1)$$

$$3\overline{I}_{0,R_1} = \overline{I}_F - \overline{I}_{B,1} - I_{C,1} \quad (2)$$

$$3\overline{I}_{0,R_1} = 3\overline{I}_0 + \overline{I}_{B,2} + I_{C,2} \quad (3)$$

$$3\overline{I}_{0,R_2} = \overline{I}_{B,2} + I_{C,2} \quad (4)$$

For selective protection, $I_{0,R2}$ must be below the pick-up value of the EF setting during the fault in the first feeder. The neutral earthing resistance of the system and capacitance of the cable used may cause the magnitude of $3I_{0,R2}$ seen in the second feeder to increase; therefore, $3I_{0,R2}$ may exceed the pick-up value causing the relay R_2 trips. One of the first methods applied to solve this problem is to increase the pick-up values of the relays that cause sympathetic tripping. Despite its simplicity, this method

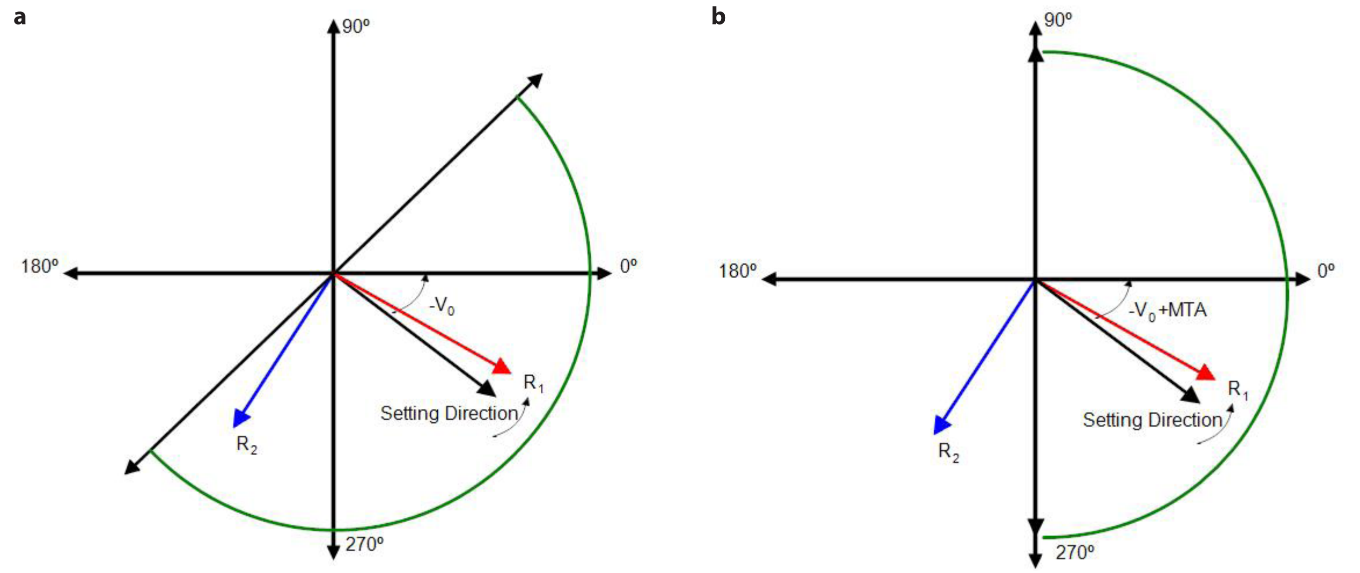

Figure 2. a, b. VPDE method (a) without MTA setting (b) with MTA setting

is not effective because it causes blinding on this feeder in the case of high impedance faults. The other method is to use a DEF relay. With help of directionality, sympathetic tripping is prevented by checking the angle information and the current magnitude. Many direction determination algorithms have been developed and implemented in the literature. The DEF protection algorithm determines the direction of the fault current by comparing it with a reference signal. The reference signal can be current or voltage. DEF protection algorithms can be classified into three categories: current–current comparison, current–voltage comparison, and symmetrical component parameters comparison [13, 14]. Conventionally, DEF protection algorithm is a vectoral comparison of the zero-sequence voltage (V_0) of the common busbar and I_0 currents of each feeders' heads. This is known as the voltage polarized directional element (VPDE) method in the literature. If the setting values are calculated correctly, it is successfully applied in the field, but the need for a voltage transformer is a disadvantage in terms of both physical layout and cost. This situation increases the motivation to develop current–current comparison methods. Studies on the application and comparison of different methods based on zero-sequence to DSs are still ongoing [15]. The application of the VPDE method is shown in Figure 2. The zero-sequence voltage angle generates the limits of operating area, adding +90˚ and −90˚. The operating area of the relay is between $\angle$-V_0 + 90˚ and $\angle$-V_0 − 90˚. These boundaries change with angle settings known as maximum torque angle (MTA). MTA is a legacy from mechanical relays. MTA is also called as relay characteristic angle in digital relays. It can be seen from Figure 2a that both I_0 vector of the faulty and healthy relays are located inside the operating area, if MTA settings are neglected. In this case, the directional discrimination of the DEF relay is lost, and selective protection is not provided. After proper MTA adjustment, the new operating area changes between $\angle$ -V0 + 90˚ + MTA and $\angle$ -V0 − 90˚ + MTA, and, directional discrimination is provided between faulty and heathy feeders as indicated in Figure 2b. The importance of the suitable MTA setting for selectivity is clearly seen in Figure 2. The empirical formula based on experimental studies is given by Equation (5) [16],

$$MTA_V = \text{acot}\left(\frac{3R_G}{X_{0T}}\right) - SFA + 90° \qquad (5)$$

where R_G is the neutral earthing resistance, X_{0T} is the zero-sequence reactance of the transformer, and SFA is the safety criteria. In systems where feeders are fed from the same transformer, the MTA setting given in Equation (5) cannot always provide selectivity. Different MTA values may also be used in field applications. Studies on determining optimum MTA value can be found in the open literature [17]. An alternative suggestion is to set the MTA value to 0° in a system with earthed through resistance, 45° at the distribution level, and 60° at the transmission level in a directly earthed system [18]. Even if the effect of neutral earthing resistance is taken into account in angle settings, it is seen that the effect of cable cross-section are and cable length is not evaluated. In this study, the effect of cable cross-section area and feeder length is also investigated.

Methods

Magnitude and angle of the I_0 vector seen by the DEF relays are affected by parameters such as neutral earthing resistance, cable cross-section area and feeder length. For this reason, it is essential to know how the magnitude and angles behave in a faulty and healthy feeder. In the system given in Figure 1 for parametric analysis, feeder lengths are increased from 1 to 40 km equally in each feeder with the step of one kilometer. Neutral earthing resistance is varied between 1 Ω -100 Ω. For comparison purposes, 240 mm^2 single core XLPE cable is used as underground cable. Parametric analyzes have been performed only for the four-feeder case but can easily be expanded. For each earthing resistance and feeder length scenario, SLEF occurred at the end of the first feeder, and the I_0 and V_0 vectors seen from DEF relays obtained. The contours

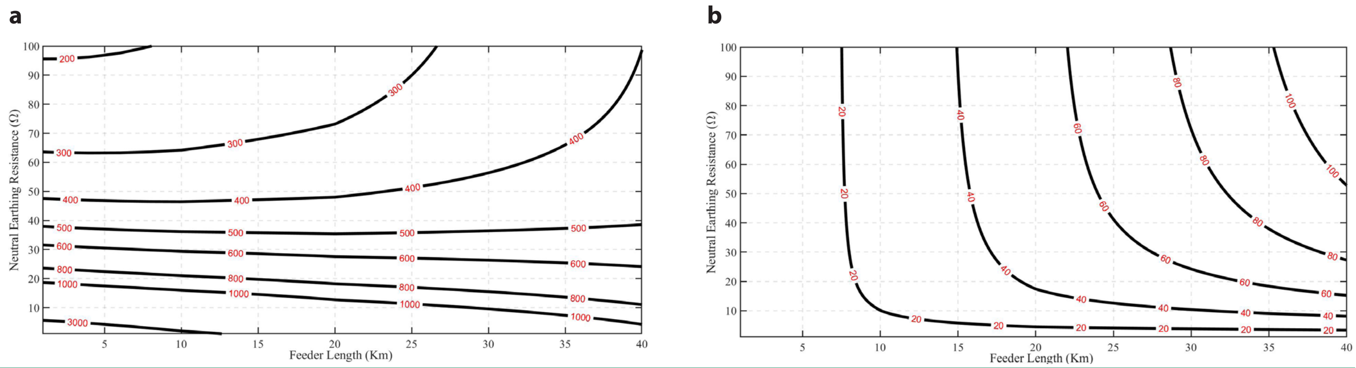

Figure 3. a, b. EF current distribution for four-feeders system (a) Faulty feeder (b) Healthy feeders

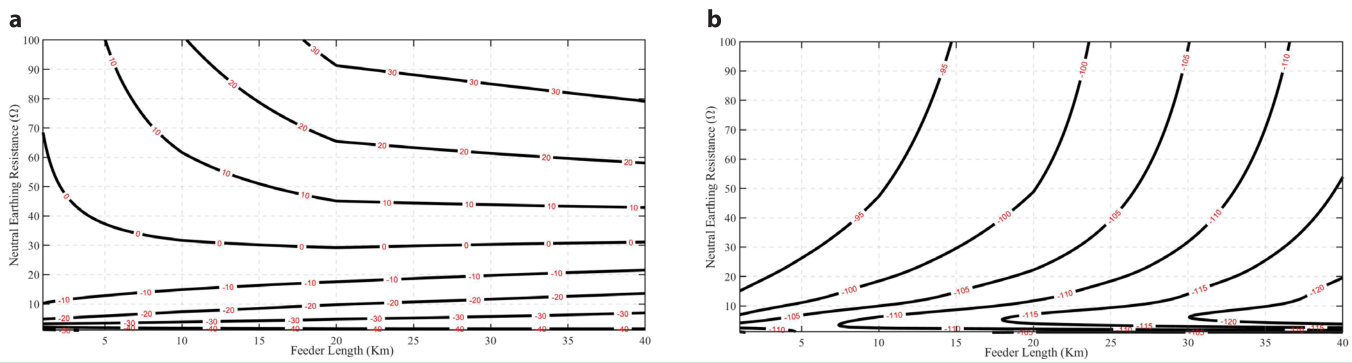

Figure 4. a, b. EF current angle distribution for four-feeders system (a) Faulty feeder (b) Healthy feeders

of I_0 magnitude of the faulty and healthy feeders in four-feeder system according to the earthing resistance and feeder length is given in Figure 3.

The variation of the magnitude of I_0 current vector seen in the faulty feeder according to the feeder length and neutral earthing resistance is given in Figure 3a. It is expected that the magnitude of the current seen by the relay will decrease with increasing feeder length. Up to 600 A limit (about 30 Ω), the current magnitude decreased with increasing feeder length. However, the effect of capacitive current becomes apparent at 400 A limit. Accordingly, with the increase in feeder length, the current is also increased. It is seen from Figure 3a that the current magnitude increases with the increase of feeder length at the limit of 200 A and 300 A. The variation of the magnitude of I_0 vector seen in the healthy feeder according to the feeder length and earthing resistance is given in Figure 3b. As can be seen, with increasing feeder length, current magnitude increases. Similarly, for a fixed feeder length, increase in the neutral earthing resistance causes the current magnitude to increase. In order to prevent sympathetic trips in the healthy feeders, the EF pick-up setting of the relay can be adjusted using these curves. It should not be forgotten that feeders can be protected non-directional relay for specific neutral earthing resistance and feeder length [19].

In four-feeder system, angle changes of the faulty and healthy feeders depending on neutral earthing resistance and feeder length are given in Figure 4. It can be seen from Figure 4a that I_0 seen in the faulty feeder shows both inductive and capacitive character. In general, it can be interpreted that the faulted feeder vector is located into the first and second region in the complex plane. However, as seen from Figure 4b that EF current in the healthy feeder located into the third region. This information provides verification about reverse direction of capacitive currents. After obtaining faulty and healthy feeders magnitudes and angles information, the reference angle is needed for the relay to make a decision. For reference angle, zero sequence voltage angle, V_0, should be obtained from the common busbar and the reference angle should be adjusted. Using the plane in Figure 2a, voltage angle V_0 obtained for each SLEF is rotated clockwise to 0° point. Thus, healthy feeder angle removed from operating area. MTA setting recommendation is given in Figure 5. Using the curve shown in Figure 5, DS operator can define MTA angle suitable for the system parameters to the DEF relay and provide selective protection. For example, in a system where the neutral earthing resistance is 20 Ω, if the feeder length is 15 km, MTA adjustment curve corresponds to the region between 10˚ and 15˚. For this scenario, MTA can be set to 15˚. Using a value such as 0˚ or 60˚, which does not take into account the effect of cable cross-section area and cable distance in MTA settings and suggested by various studies, may cause relay mal-operations. Similarly, high values of MTA may cause faulty feeder I_0 vector to be removed of the operating area. For this reason, care should be taken to select the appropriate parameters for the system to be protected while setting MTA.

Table 1. Earth fault results for 62 node networks with proposed settings

		Fault Location											
Relay Parameters		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
I_0 Magnitude	R_1	935.19	945.36	954.64	5.84	5.84	6.14	5.42	5.75	5.92	4.95	5.46	5.94
	R_2	12.99	13.13	13.26	899.16	899.16	945.29	11.60	12.31	12.67	10.59	11.68	12.71
	R_3	26.69	26.98	27.24	25.67	25.67	26.99	834.00	885.52	911.49	21.75	23.99	26.11
	R_4	44.99	45.48	45.93	43.28	43.28	45.50	40.17	42.66	43.91	760.82	839.11	913.25
I_0 Angle	R_1	-1.21	-0.73	-0.30	-96.45	-95.64	-94.32	-99.30	-97.00	-95.82	-102.60	-99.19	-95.92
	R_2	-94.83	-94.36	-93.92	-3.26	-2.45	-1.13	-99.31	-97.01	-95.83	-102.62	-99.20	-95.93
	R_3	-94.88	-94.41	-93.97	-96.52	-95.70	-94.39	-6.95	-4.65	-3.47	-102.67	-99.25	-95.98
	R_4	-95.01	-94.54	-94.10	-96.64	-95.83	-94.51	-99.49	-97.19	-96.01	-11.38	-7.96	-4.69
R_1 MTA10°	Maks	95.18	95.66	96.09	93.55	94.36	95.68	90.70	93.01	94.18	87.40	90.81	94.09
	Min	-84.82	-84.34	-83.91	-86.45	-85.64	-84.32	-89.30	-86.99	-85.82	-92.60	-89.19	-85.91
R_2 MTA10°	Maks	95.18	95.66	96.09	93.55	94.36	95.68	90.70	93.01	94.18	87.40	90.81	94.09
	Min	-84.82	-84.34	-83.91	-86.45	-75.64	-74.32	-79.30	-76.99	-75.82	-92.60	-89.19	-85.91
R_3 MTA15°	Maks	100.18	100.66	101.09	98.55	99.36	100.68	95.70	98.01	99.18	92.40	95.81	99.09
	Min	-79.82	-79.34	-78.91	-81.45	-80.64	-79.32	-84.30	-81.99	-80.82	-87.60	-84.19	-80.91
R_4 MTA20°	Maks	105.18	105.66	106.09	103.55	104.36	105.68	100.70	103.01	104.18	97.40	100.81	104.09
	Min	-74.82	-74.34	-73.91	-76.45	-75.64	-74.32	-79.30	-76.99	-75.82	-82.60	-79.19	-75.91

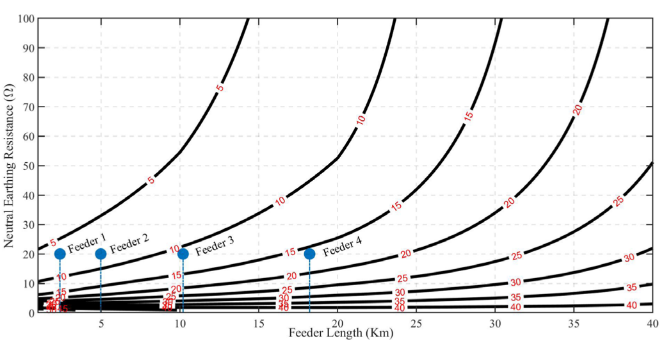

Figure 5. MTA setting curves

Test System

In this section, proposed pick-up current and MTA setting are presented in order to provide selective protection of the sample substation by using the contour curves obtained in the previous section and the performance of the recommendations has been examined with the analysis. The sample substation has Yn/Yn connection type at a voltage level of 154/34.5 kV, high voltage side is solidly earthed and medium voltage side is earthed through 20 Ω resistor. The substation has four feeders. 240 mm^2 single-core underground cable is used. Sample DS consists of 62 nodes in total. The total lengths of the four feeders and the topology of the DS are shown in Figure 6. The fourth feeder, which is the longest one, has a capacitor bank for power factor correction. In order to evaluate the impact of the fault location, SLEF is calculated at twelve different locations. Fault locations are marked in Figure 6.

I_0 vector seen by the relays in the feeders and V_0 vector of the common busbar are given in Table 1 for each fault location scenario. For 20 Ω neutral earthing resistance, it is seen from Figure 3a that EF current magnitude in faulty feeder are in the range of 600 A-1000 A depending on the feeder length. It would be appropriate not to set the pick-up current values above these limits. Using the healthy feeder current magnitude contour curves given in Figure 3b, it is expected that currents below 20 A will be seen at the first feeder for 2.38 km length and 20 Ω neutral earthing resistance. When Table 1 is examined, the value of 20 A is never exceeded in the relay R_1 in faults occurring outside its protection zone. Also, in the first feeder, there is no capacitor bank that is expected to increase the current seen by the relay in the healthy feeder. Therefore, relay R_1 can be set at 20 A. Currents below 20 A are expected in the second feeder. It is seen from Table 1 that relay R_2 relay does not reach 20 A value in faults occurring outside its protection zone. Therefore, the relay R_2 relay can also be set at 20 A. For the third feeder with a length of 10.19 km, EF current determined in Figure 3b corresponds to the area between 20 A and 40 A. It would be appropriate to set relay R_3 at 40 A. Since the fourth feeder is the longest one, it is the most

Table 2. Proposed relay pick-up and MTA settings

	R_1	R_2	R_3	R_4
Pick-Up	20 A	20 A	40 A	60 A
MTA	10˚	10˚	15˚	20˚

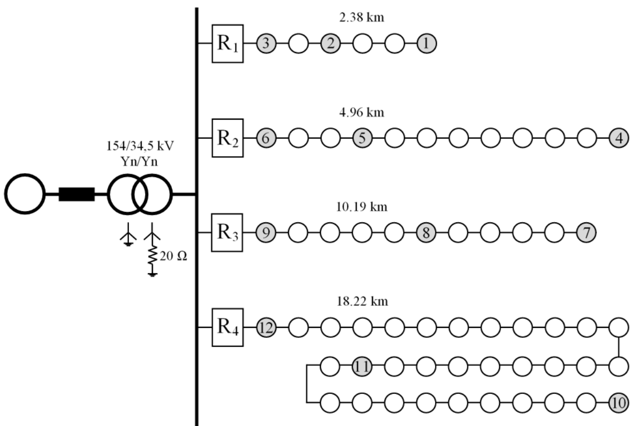

Figure 6. 62 node distribution network

problematic one for EF protection. The fourth feeder with a length of 18.22 km located into the 40 A region. However, the capacitor bank connected to the feeder head causes the magnitude of the EF current seen at relay measuring point to increase during SLEF. Therefore, it is expected to obtain a higher EF current than the obtained one from the curve. For this reason, it would be suitable to set it to a value higher than 40 A. Therefore, relay R_4 is set to 60 A. The area for all feeders are marked in Figure 5. The first and second feeders are in the area between 5˚ and 10˚. MTA 10˚ can be selected for relays R_1 and R_2. The third feeder is in the area between 10˚ and 15˚. It would be appropriate to set MTA 15˚ for relay R_3. The fourth feeder is in the region between 15˚ and 20˚. It is appropriate to choose MTA 20˚ for relay R_4. The settings for all DEF relays are summarized in Table 2. MTA setting formula given in Equation (5) implement to 62 node DS. MTA is calculated as 46° for all DEF relays. Selective protection is provided for this MTA setting in 62 node resistance earthed DS. One should remember that parameter change in DS (i.e. earthing resistance, parallel feeder numbers or cable cross-section area) results changing in MTA setting. Thus, similar curve-based analysis must be carried out determine the boundaries of MTA setting for selective DEF protection.

Conclusion

In this study, the necessity of DEF protection in radial DS where underground cables are, extensively, used is presented. DEF relays operate as non-directional EF relay if appropriate MTA setting is not adjusted. In the four-feeder radial distribution system, the vectoral behavior of the faulty and healthy feeders under SLEF is investigated by obtaining contour lines in a wide range neutral earthing resistance and feeder length pairs. Utilizing contour curves, MTA setting suitable for the VPDE method is obtained according to the neutral earthing resistance and feeder length. With the help of these curves, a methodology for setting DEF relays is proposed. Using the curves obtained on a sample DS, the pick-up and MTA settings of the DEF are arranged. When the SLEF results are examined after the suitable relays setting, the system is selectively protected at all fault location scenarios. Thus, these curves may be used as a tool by DS system operators for properly setting of DEF relays depending on the number of parallel feeders, cable cross-section and feeder length. However, since the capacitor bank in the system causes the magnitude of the I_0 vector seen by the DEF relay to increase, it is suggested that the pick-up current of the feeders with the capacitor banks should be set to a value above the one obtained from the curve.

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RESEARCH ARTICLE

Emerging Financing Tools for Renewable Energy Investments

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ABSTRACT

Renewable energy sources (RES) are one of the important sources that can be used for transition to a sustainable low carbon economy. With increasing use of RES, significant contribution can be made to the Paris Agreement's goal of keeping global warming below 2 °C. In recent years, the increase in RES investments has revealed different financing options. Crowdfunding, green bonds, and green loans financing tools are becoming increasingly popular tools for financing RES investments. By using these financial tools, financing opportunities of RES investments have been diversified. In recent years, these financing tools are also being increasingly used in Turkey. To increase the use of crowdfunding in RES investments, dedicated crowdfunding platforms should be established. An important issue in green bonds is external opinion; therefore, introducing a legal obligation will increase investors' interest in green bonds and their trust in the bond issuer. In addition to the existing opportunities in green loans, tax incentives can be provided to contribute to RES investments.

Keywords: Renewable energy, renewable energy finance, crowdfunding, green bond, green loan

Introduction

Owing to the dominant role of fossil fuels in meeting global energy demand, there has been a rapid increase in CO_2 emissions [1]. Fossil fuels are finite sources and global warming occurs mainly because of increased use of these sources. Increasing levels of global warming have encouraged the use of renewable energy sources (RES) in the world [2-4].

Global energy consumption has increased by an average of 1.6% annually between 2014 and 2019, and the use of RES has increased by an annual average of 12.5% between the same years. In 2019, 36% of the global energy demand was met by natural gas, 21% by oil, and 41% by RES [5].

With respect to the reduced electricity production costs of RES power plants and the adoption of policies encouraging the transition to renewable energy, a rapid growth has been recorded in electricity produced from RES [5].

Owing to the developments in technology, competitive supply chain, and experience gained, costs of electricity generation from RES have decreased significantly in the last 10 years. The share of RES sources within the installed power plants has been increasing. Approximately 72% of the newly commissioned power plants in 2019 were RES power plants [6].

The world population is expected to increase by 1.7 billion by 2040 and, consequently, the global energy demand will grow by a quarter. The aim is to reduce the share of energy production using fossil fuels by 40% by 2030 and to increase the share of RES in energy production by 60% by 2040 [7].

The Paris Agreement, which was adopted in 2016, started a new era in the global climate regime. The agreement aimed to reduce the global average temperature increase below 2 °C and, if possible, to limit it to 1.5 °C. In this period, it was decided that countries that signed the agreement will take measures to reduce their greenhouse gas (GHG) emissions [8]. Country-specific contributions that will reduce GHG emissions are at the center of agreement. The use of RES is one of the most important ways to meet the requirements of this agreement [9].

Competitive advantage in the renewable energy sector offers an important opportunity for Turkey, which is rich in RES potential.

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Many technical, economic, and environmental problems caused by using fossil sources can be eliminated by utilizing rich RES potential of Turkey [10].

Turkey's installed power shares by source type at the end of 2019 are given in Fig. 1. Turkey's total capacity was 93,022.7 MW and installed power was 46,441.8 MW in 2019, which constituted 49.92% of the total capacity. The installed power consisted of RES including hydroelectric power plants (HPPs) [11].

Turkey's GHG emissions continue their upward trend. The total GHG emission value, which was 219.4 million-ton (Mt) CO_2 equivalent (eq.) in 1990, increased by approximately 138% and reached 520.9 Mt CO_2 eq. by 2018. According to 2018 emissions data, energy-related emissions ranked first with a share of 71.6%. Energy-related emissions had the largest share in the total CO_2 emissions; 35.5% of the total CO_2 emissions in 2018 originated from electricity and heat generation and 85.8% originated from the energy sector [8].

Turkey signed the Paris Agreement, but has not yet ratified it. In 2015, Turkey submitted its Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change secretariat. According to the INDC, in business as usual (BAU) scenario, Turkey's emissions would be 1,175 Mt CO_2 eq. in 2030. In its commitment, Turkey pledged to reduce its GHG emissions by 21% less than the BAU scenario by 2030 [12].

Turkey determined the plan and policies to be implemented for the INDC. Most of the measures to be taken in the energy sector involve RES usage targets [12]. Decarbonization of the energy sector, which has a large share in GHG emissions, will accelerate with increase in use of RES [13].

RES has become economically competitive with fossil sources, and the trend of decreasing production costs will continue in the coming years [6].

RES is considered to be an efficient way to limit the global average temperature increase. In addition to having a great potential in reducing the effects of climate change, these sources contribute to social and economic development, energy accessibility, energy supply security, and reduction of energy-related negative effects on environment and health [1].

There have been positive developments related to RES utilization for electric power generation in Turkey; Most importantly, installed power has increased. However, the rate of RES other than HPPs, especially wind, remains low [14, 15].

Main Points

- Recently popular financing tools in RES investments are crowdfunding, green credit and green bonds.
- There isn't crowdfunding platform at RES area in Turkey.
- The most important criterion for the investor in green bonds is the external opinion known as the second party.

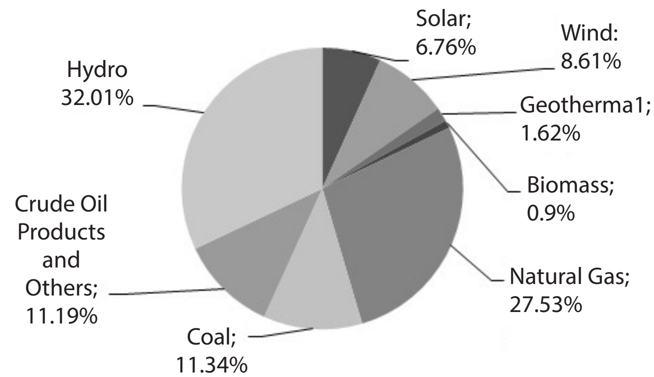

Figure 1. Installed power shares by source in Turkey

Increasing the use of RES in electricity generation can help Turkey reduce its carbon energy conversion rates. Thus, Turkey will be able to contribute to the goal of keeping the global temperature increase below 2°C, as decided in the Paris Agreement [9].

In addition to determining national contributions to reduce GHG emissions, the Paris Agreement emphasizes the financing of measures to be taken by all countries to reach the determined 2°C target. Financial resources are needed to achieve the goals set by the Paris Agreement. Article 2.1c, one of the three long-term objectives of the agreement, is "to provide a financing flow with a way towards low GHG emissions and climate-resilient development [16]."

This article emphasizes the importance of the joint contribution of all contractors (public, private, national, and international) in providing the necessary financing in combating climate change [17]. The governments participating in the agreement can provide the financial flow targeted by the Paris Agreement with arrangements and practices they make under various titles. These arrangements and practices include voluntary tools like green bonds [17].

To reach the 2°C target determined by the Paris Agreement, an investment of $53 trillion is required until 2035 in the energy sector. In this context, many financial tools are needed to use public and private sector resources to achieve this goal. In recent years [9], green bonds are one of the most common financial tools used to finance green projects using private sector resources.

The initial costs of RES-based energy investments are high compared with fossil-based power plant investments. There are various options for financing RES projects. Efforts to prevent climate change have increased the interest in the concept of green finance [9]. Grants, bank loans, leasing, export credit, and Power Purchase Agreements (PPAs) for renewable energy are some of these tools. Crowdfunding, green bond, and green loan mechanisms are other important financing tools that have come forward in recent years.

In this article, emerging financing tools used in the financing of renewable energy investments, are examined. In the second section of the article, general financing tools for renewable energy have

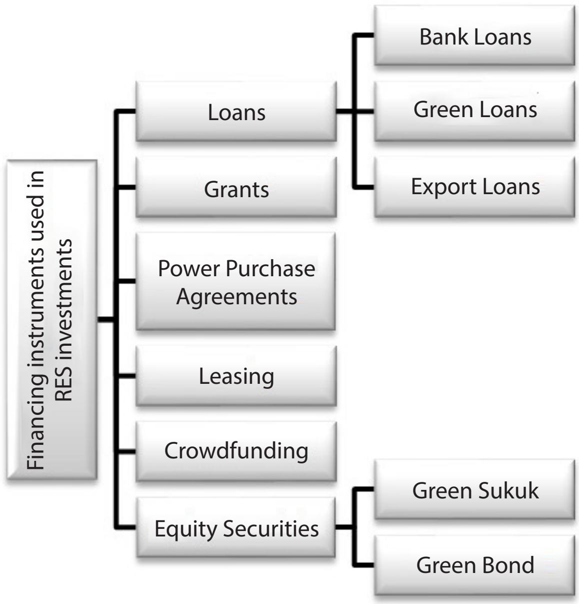

Figure 2. Renewable energy investments financing tools

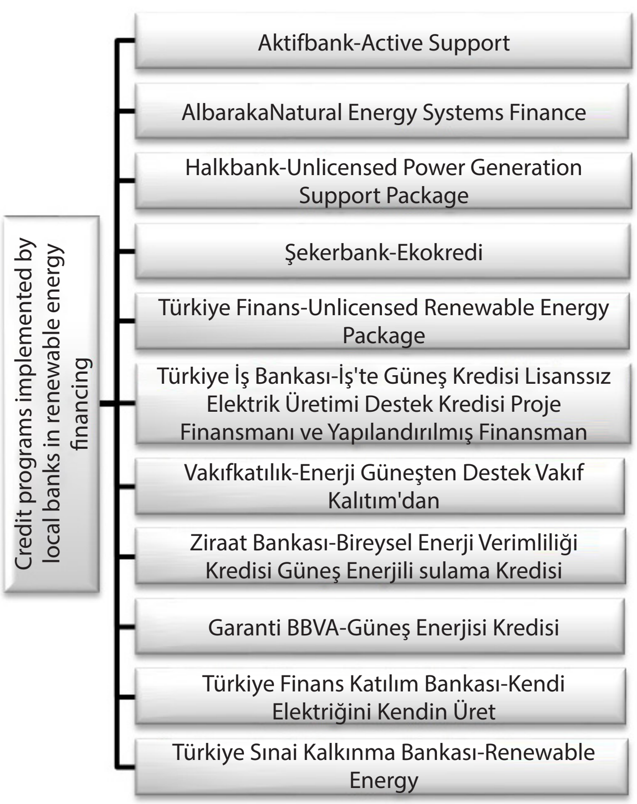

Figure 3. Green loan programs of local banks in renewable energy financing

been explained and classification of these tools has been made. In the third section, crowdfunding, green bonds, and green loans, which are emerging financing tools in renewable energy investments, are explained. The fourth section of the study is conclusion and discussion, and the final section describes policy recommendations.

Renewable Energy Investment Financing Tools

Today, external financing needs of renewable energy investments are met by various financing tools. Fig. 2 shows renewable energy investments financing tools.

Grants are unrequited funds provided by international organizations and public institutions for small- and medium-sized enterprises within the scope of the project [18]. The grants used in renewable energy investments aim to reduce the total financial cost of the project by shortening the project's depreciation period [19].

PPA is a new financing method that enables the diversification of the financing models of RES projects. This mechanism has the characteristics of a medium and long expiry energy supply agreement. In this mechanism, an organization that wants to meet its electrical energy demand with RES and an electricity generation company make a PPA. This mechanism is an alternative electricity supply mechanism that provides ease of financing to the facilities to be established and a long-term regular income flow for the existing facilities. Companies' interest toward this mechanism has increased in recent years [14].

Leasing is a long and medium expiry investment loan for the use and acquisition of tools or heavy machinery equipment [20]. In leasing, 1% value added tax is applied on many equipment and machines [21].

Loan is the granting of a certain amount of purchasing power to legal or natural persons with applicable interest for a certain period of time. Different loan programs are available in local banks [Fig. 3] in Turkey for renewable energy sector [22].

Export credit is a type of credit provided for making foreign currency earning transactions or for small and medium-sized export enterprises [23]. For export credit, Germany: HERMES, Switzerland: Eurasian Resources Group, Austria: Oesterreichische Kontrollbank AG (OKB), Belgium: OND, Spain: Compañía Española de Seguros de Crédito a la Exportación, United States: Export-Import Bank of the United States (US EXIM), Italy: Servizi Assicurativi del Commercio Estero, France: Compagnie Française d'Assurance pour le Commerce Extérieur , Japan: Ministry of International Trade and Industry, Finland: FINNVERA, Denmark: EKM, Netherlands: Nederlandsche Credietverzekering Maatschappij, South Korea: The Export-Import Bank of Korea KEXIMBANK, Australia: Export Finance Australia (EFIC), United Kingdom: Export Credits Guarantee Department, Sweden: Exportkreditnämnden (EKN), Turkey: Export Credit Bank of Turkey (EXIMBANK) banks have established their own constitutions [24]. Turkish EXIMBANK allocated 2.2% of its loans to energy sector in 2019 [25].

Crowdfunding is the gathering of the masses to collect the money required for the projects of other communities or organizations through the internet and to provide the necessary financing for these projects [26]. The four models of crowdfunding are as follows: debt-based, donation-based, reward/gift-based, and equity-based [27]. Donation-based, equity-based, and reward/gift-based models are used in Turkey [28].

Green bonds are debt securities with interest rates used to allocate capital to environmentally beneficial enterprises that fall under the concept of green projects such as energy efficiency, biodiversity conservation, clean transportation, renewable energy, sustainable water management, and pollution prevention and control [29].

Green sukuk is an interest-free financing tool used to finance renewable energy and sustainable and environmentally beneficial projects [30].

Green loans are special development loans developed by international development organizations, usually offered to projects that commit to reducing one of the social, economic, cultural, and environmental degradations in the fields of renewable energy, energy efficiency, and the environment [31].

Emerging Financing Tools for Renewable Energy Investments

To better support renewable energy investments, new financing tools have been introduced. Crowdfunding, green bonds, and green loans are recently prominent financing tools for financing renewable energy investments.

Crowdfunding

Crowdfunding is a financing model in which entrepreneurs obtain their funds directly by finding investors through internet platforms instead of bank [32]. There are four different types of this financing model. Donation-based crowdfunding is a type of funding that is used in nonprofit projects, where the money is not taken back and only donated. Reward/gift-based crowdfunding is the most used funding today. It is the type of funding where the entrepreneur offers gifts or services to the investor. These services are worth the amount of funding provided by the investor. Equity-based crowdfunding is a type of funding in which the investor has a share in the project in addition to providing financial support to the entrepreneur. Debt-based crowdfunding is a type of funding that entrepreneurs make in the form of loans, on condition that they repay money, such as loans from banks. Apart from these, there are hybrid models. The hybrid model is a model in which more than one type of crowdfunding is included in the same project; the investor chooses the model they want and provides funds [33].

Crowdfunding is an unconventional financing model. It collects the masses together through the internet. The use of internet platforms for crowdfunding reduces transaction costs. Technological developments and the spread of social media have increased the power of the masses. The internet reaches around one-third of the world. Therefore, the crowdfunding mechanism is not limited to a specific geographic region. In conventional financing models, few professional investors provide large amounts of financing to projects. In contrast, in crowdfunding, large communities finance many small and large-scale projects by making small contributions. Even small projects that banks cannot finance can be financed with crowdfunding. Crowdfunding provides many social, environmental, and economic benefits, as it involves local communities in their funding processes. In this way, it prevents the "not in my backyard" phenomenon [34].

Table 1. Usage rates of crowdfunding types in of renewable energy sector [36]

Crowdfunding type	Usage rate (%)
Debt-based	56
Reward/gift-based	24.2
Hybrid	10.1
Equity-based	9.7

The crowdfunding market continues to grow. Having a capacity of $53 million in 2010, this market reached a market capacity of $16 billion in 2014 [35]. The crowdfunding mechanism can be potentially used in financing RES projects, which play an important role in combating climate change.

Since 2009, significant crowdfunding platforms focusing on RES projects have started to appear. The "Trillion Fund" platform provided approximately $122 million as funds for RES projects in 2011. This figure shows the potential of the crowdfunding mechanism for RES projects [35].

Crowdfunding works in the form of investors providing funds and advice through platforms of entrepreneurs' ideas and initiatives in the RES field [35]. The usage rates of crowdfunding types in renewable energy sector are given in Table 1 [36].

Equity-based and debt-based crowdfunding are made with special regulations according to the legal legislation of each country. Donation-based and reward/gift-based crowdfunding types are evaluated within the scope of e-commerce, because they do not pose a potential risk to investors and entrepreneurs. In reward-based crowdfunding, the aim of the investor is to involve himself in the project development process instead of generating revenue. Therefore, the investor-entrepreneur relationship is more important in reward/gift-based crowdfunding than in other types of crowdfunding. Trust between investors and entrepreneurs needs to be stronger than the trust in traditional e-commerce practice. In countries such as the United States, where crowdfunding is popular, social networks are very important. With the help of social networks, investors can be accessed for feedback of the entrepreneurs' projects. These feedback comments presented on social networks reveal the entrepreneur's potential. In this way, by providing interpersonal interaction, a sense of trust is developed between investors and entrepreneurs [37].

The most used platforms in the field of renewable energy in the world are Village Power, Collective Sun, Re-Volv Solar Seed Fund,

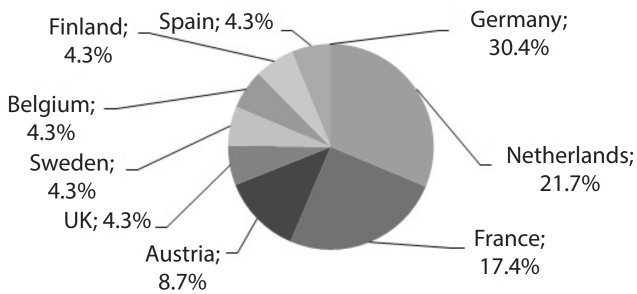

Figure 4. Share of crowdfunding investments made in the field of wind on platforms in Europe

Cleanreach, Divvy Green, and SunFunder. The Village Power platform, founded in 2014, has provided a total of $ 5,377,400 for renewable energy projects; it is the platform that has financed most projects to date [38].

Incentives for using renewable energy have been increased to prevent climate change in Europe. In this context, the CrowdFundRes project has been realized. Within the scope of the project, a total of 23 crowdfunding platforms under the name of renewable energy systems have been established in European countries. With the help of these platforms, support was provided for wind and solar power plant projects [39].

Fig. 4 shows the distribution of crowdfunding investments made in the field of wind on platforms in Europe.

In France, a renewable energy project called Solar PV was realized with the contribution of 438 investors through the Oneplanetcrowd and Lumo platforms, collecting €0.8 million. Likewise, Solar PV, by collecting €1 million through 291 investors with the Oneplanetcrowd platform in the Netherlands, Wind Turbine with a fund of €4,475 with the support of 1,013 investors with the Abundance Investment platform in the United Kingdom [40]. In Spain, Vortex Bladeless Turbine projects were implemented with 1,300 investors, collecting €0.071 million with the Vortex Bladeless platform [41].

In Turkey, there are nine crowdfunding platforms that are already operating. The most preferred of these platforms is Arıkovanı, which uses the donation-based crowdfunding model and was established in 2019. Arıkovanı has financed 464 different projects with a total fund of 6 million TL [42]. The Fonbulucu platform, which adopts donation-based crowdfunding, has funded 20 projects by collecting 4.8 million TL [43]. Fongogo, a reward/gift-based platform, has funded 2.4 million TL to 130 projects since 2013 [33]. crowdFON is the first crowdfunding platform established in Turkey that uses the reward-based crowdfunding model; it has funded many fields such as art, technology, music, and literature [44]. The Ideanist platform, which provides funds for projects in the fields of innovation and technology provided to bring to life, collected a total of 335,154 TL with its donation-based crowdfunding type, enabling nine projects [45]. The Startupfon platform, which funds 27 projects, uses equity-based crowdfunding in software, mobile, internet and advanced technologies [46]. A crowdfunding platform that solely allows investment in renewable energy does not exist in Turkey.

Green Bonds

Green bonds are bonds that provide funds for the financing of projects collected under the name of green projects. Proceeds of green bonds are earmarked for green projects which cover renewable energy, energy efficiency, clean transportation, sustainable management of natural resources, biodiversity conservation, and pollution prevention and control. Generally, 75% of the proceeds from green bonds are invested in the fields of energy efficiency and renewable energy [29].

The green bond process takes place in line with the standards set in the guide that includes the green bond principles of the issuer. It starts with the issuer choosing the appropriate project from the green projects in these standards. The investor institution or organization tests compliance with the green bond principles itself or with a consultant. If compliance is achieved, the investment process begins, and all proceeds obtained from bonds are transferred to a specially designated account to be used in the specified green project. Payments are made from this account depending on the expiry period, the time, and the amount of payment, which vary according to the project. The issuer executes the project with the revenues obtained [47].

Green bond principles consist of four main stages. The first of these stages is “use of proceeds.” The purpose of the use of proceeds is to finance or refinance green projects. The second stage is the “process for project evaluation and selection.” At this stage, projects are evaluated according to green categories. The third stage is “management of proceeds.” The purpose of management of proceeds is to ensure that funds from green bonds only finance green projects. In reporting stage, issuers are requested to make the whole green project status in annual reports. Reporting with the help of an external opinion is a process required by investors. The principles in the green bond principles stated are voluntary and have no obligation and the issuer is expected to do voluntarily [48].

Investments made in green bonds are expected to be included in the concept of green projects. Otherwise, the reputation of the issuer may be damaged [49].

Investor concerns about “green washing” have increased in recent years. Therefore, green bond certificates are issued to help the green bond market expand and to gain investor trust. There is no single standard for certification. The “green bond principles” is the most widely used certification system [26].

The number of green bonds certifications has increased. Although the rate of green bonds receiving an external opinion was 65% in 2015, it increased to 82% in June 2017 [26]. In the global bond market with a market volume of $90 trillion, the volume of green bonds in 2017 was approximately $100 billion. To promote the in-

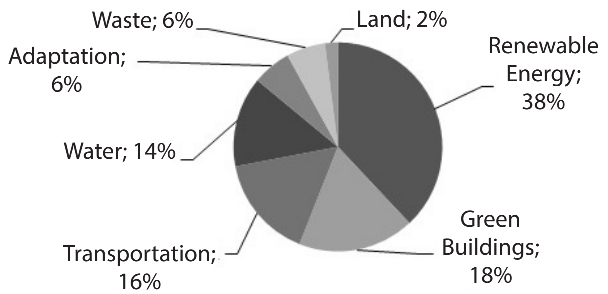

Figure 5. Global share of green bonds by sector [51]

terest of investors in the green bond market, a single certification system with high credibility should be developed [26].

The first green bond in the world was exported by the World Bank and the European Investment Bank in 2007 under the name of "Climate Awareness Bond [29]." Poland issued the first green bond in 2016; Fiji, France, and Nigeria issued their first green bond in 2017; Belgium, Indonesia, Ireland, Lithuania, and Seychelles issued their first green bond in 2018 [50]. Fig. 5 shows the global share of green bonds by sector [51].

The first green bond issued in the United States in 2009 was "Clean Renewable Energy Bonds." It was designed in the form of coupon payments to increase marketability. Investors were provided with tax reductions in the amount of coupon payments instead of coupon payments. All funds obtained from this bond were used only in wind, geothermal, solar, and biomass projects [52].

Since 2007, Europe has issued green bonds worth €122 billion in total with 144 issuers. Nelja Energia, a renewable energy company in Estonia, issued the first green bond of €50 million to finance solar, hydro, wind, and biomass projects in 2015 [53].

Turkey has realized its first green bond issuance in 2016. The first green bond issuance worth $300 million with a maturity of 5 years was executed by TSKB. Approximately 42.6% of the proceeds raised from this issuance were used in renewable energy; the remaining shares of the proceeds used were used as follows: 10.7% in health, 24.9% in electricity distribution, 1.8% in energy and resource efficiency, and 20% in ports [31]. Garanti BBVA executed a green bond issuance worth $50 million with a maturity of 5 years in 2019. Proceeds from this issuance were allocated for wind and solar power plants [54]. Yapı Kredi bank executed a green bond issuance worth $50 million with a maturity of 5 years in 2020 and proceeds from this issuance were allocated solely for renewable energy investments [55].

Green sukuk started to be used as an interest-free financing model by Indonesia in 2018 to finance renewable energy, environmentally friendly, and sustainable projects [56]. Malaysia, which attaches importance to environmentally friendly projects owing to the high number of climate disasters, is in the first place in green sukuk development. The most distinctive feature of green sukuk is that it has the same conditions as green bonds but is interest free [57]. The first green sukuk issuance worth of 50 million TL with a maturity of 1 year was executed by TSKB in 2020 on behalf of Zorlu Energy [58].

Green Loans

The definition of green loan appeared in China with the meeting of the Ministry of Environment of the People's Republic of China, the People's Bank of China, and the Banking Association of China in 2007. These organizations have published the green credit policy dictating that all banks in China should not fund companies that have excessive consumption of natural and energy resources or cause environmental pollution, provided that companies prepare projects with privileged terms [59].

Green loans are reconstruction credits developed by international development organizations specially for the fields of environment, renewable energy, and energy efficiency. The purpose of a green loan is to fund projects that undertake to reduce one of the distortions in the cultural, social, environmental, and economic areas requested by the lender. Because of this feature, it is a type of loan that differs from other loan types. In green loans, long-term advantageous payment options with low interest rates are offered to the user, who receives the loan, by evaluating their performance in the green field such as energy savings and energy efficiency [31].

In Turkey, the first foreign-funded green loan of $260 million was used in four wind power plant investments. This green loan, provided by the German investment bank (KfW) and the European Bank for Reconstruction and Development (EBRD) within the body of four Turkish banks, was in accordance with the green loan policy published by China. Green loan users were scored every year throughout the expiry of the loan according to their sustainability performance rated by the international rating agency. The points obtained are repeated every year for the pricing of the loan. Points are evaluated and subjected to a discount in interest rates. This control mechanism is used to encourage users to apply for a green loan and is included in the published legal text [31].

In Turkey, green loans through local banks are given by the EBRD, KfW, World Bank, and the French Development Agency [19]. The World Bank provides green loans with Ziraat Bank and Vakıfbank within the scope of the "SME Energy Efficiency Project" program. The French Development Agency conducts "Renewable Energy Loan" and "Energy Efficiency Loan" programs with Halkbank. Besides these (within Turkey), İş Bank with European Investment Bank created "the European Investment Bank Loan" program. Green loan programs started by EBRD with local banks are shown in Table 2 [19].

Discussion

Many mechanisms used for financing renewable energy investments are available. Crowdfunding has increased initiatives and investments, because it facilitates access to finance, especially in Europe and the United States. The most distinctive feature of crowdfunding compared with other types of financing is that it allows investors to find projects and entrepreneurs to find financing by eliminating the distance problem with the help of social net-

Table 2. Green loan program issuers by the EBRD with local banks

Bank	Green loan program
Aklease	The Turkey Sustainable Energy Financing Facility (TurSEFF)
Denizbank	The Turkish Mid-size Sustainable Energy Financing Facility (MidSEFF)-TurSEFF
QNBFinans Leasing	TurSEFF
Garanti BBVA	MidSEFF
Şekerbank	Turkish Residential Energy Efficiency Financing Facility (TuREEFF)
Turkiye İş Bankası Bank	MidSEFF- TurSEFF- TuREEFF
Vakıfbank	MidSEFF- TurSEFF
Yapıkredi	TurSEFF- TuREEFF
Akbank	MidSEFF- TurSEFF

working platforms. Crowdfunding is most popular in the United States. The number of crowdfunding platforms in Turkey is insufficient and most people do not know about this financing tool. This situation is a barrier to the development of the crowdfunding market in Turkey. Turkey does not have debt-based crowdfunding platform, but several studies are being performed on this type of crowdfunding. Equity-based crowdfunding may be active in the near future and more projects in the field of renewable energy may arise. Turkey does not have a platform specific to the renewable energy sector. Green sukuk issuance does not exist in the renewable energy field in Turkey.

Green bonds have shown a rapid development. Legally nonbinding external opinion, also known as the second party application, is an important criterion by the investor. With an external opinion, the investor wants to see the transparency they seek in the issuer. A special incentive application is not available in the renewable energy sector within the scope of the green project. In 2016, the first green bond was issued in Turkey; this shows that Turkey joined the green bond market late. With their increasing use around the world, green bonds have become an emerging market. There are no binding legal regulations for green bonds. Nonbinding international guidelines, which are to be adopted on a voluntary basis, have been adopted by some initiatives. However, to keep the development of the green bond market unobstructed, it is not subject to binding regulations currently.

Policy Recommendations

Turkey should adopt an energy policy focused on RES. Turkey can increase the utilization rates of its rich RES potential using crowdfunding, green bonds, and green credit tools.

Regulations should be imposed on debt-based and equity-based crowdfunding models. This will lead to an increase in RES investments share of crowdfunding. In the field of crowdfunding, different media platforms should be used, and awareness-raising activities should be organized for promotional purposes. Crowdfunding platforms dedicated to renewable energy sector should be established. In this way, the transition to renewable energy can be accelerated.

A green bond is a financing mechanism that is realized at the request of the issuer and investor and is within the body of institutions or organizations. For this reason, joint studies should be conducted with the support of public and private sector cooperation and civil society organizations to increase RES investments. To gain trust of the investors, instead of "external opinion" guidelines, auditing institutions or compulsory consulting firms should be established. Green bonds are not legally binding in Turkey. If the Capital Markets Board of Turkey publishes a legal basis for this financing instrument, it may increase the investments in green bonds.

Green loans should be encouraged through facilities such as technical assistance supports, tax exemptions, and tax relief. In this way, green and sustainable financing can be increased in renewable energy investments.

The government should continue its practices that encourage electricity production from RES, and private sector initiatives should be supported.

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REVIEW

A Survey on Recent Developments of Islanding Detection Techniques

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ABSTRACT

Nowadays, the power distribution system comprises distributed generators (DGs) that provide low-cost electricity and have fewer adverse environmental consequences. In some situations, these DGs continue to supply the nearby loads owing to line outage and system separations creating islands. This causes unacceptable power quality conditions. If this is not detected, it may harm the load. This type of islanding may also occur in the transmission lines because of stability issues caused by transmission line outage. If this is not detected at an early stage, the entire system may collapse. Harmful islanding needs to be detected and addressed. This study describes several recent methods and standards related to islanding detection. The acceptable voltage and frequency range, testing conditions, and maximum islanding detection time are mentioned in the IEEE1547, UL1741, and IEEE929 standards. The detection algorithms can be active, passive, hybrid, and communication based. These algorithms have been discussed in detail in this article.

Keywords: Active method, communication-based method, distributed generation, hybrid method, islanding detection, passive method; power systems

Introduction

Artificial neural networks of variable hidden layer sizes have been tested for islanding detection in IEEE 9 bus system in [1]. The neural network works as a simple classifier for separating islanding and nonislanding cases. The same methodology has been improved in [2] using probabilistic algorithm for islanding detection. Firstly, artificial neural network incorporates the selection of parameters of the hidden Markov model, which are later used for islanding detection during data unavailability. Bilateral reactive power variation is the main logic in [3] for islanding detection. This is one of the hybrid approaches for islanding detection. Characteristic analysis has been performed to obtain design parameters of the hybrid method. The method has been validated under IEEE Std 929 and IEEE Std 1547 criterion. In [4], a model component-based islanding detection method has been tested on a prototype system. A detection factor is required for this method. It can detect islanding in exact power balance condition. A fuzzy neural-based method has been implemented in [5] for calculating probability of islanding in a system where there are multiple connections with the grid. The probability is determined using active, passive, and communication-based hybrid methods. The auxiliary service required for the probability is not received in the control center. The method proposed in [6] is a hybrid method using communication and passive methods for smooth operation and stability, which is ensured by adjusting voltage and power of the generator. This method is not affected by any change in generation and load. Voltage injection in d-axis current is an effective tool for islanding detection within 810 ms in large photovoltaic system as experimented in [7] under standard situations mentioned in IEEE 1547-2008 and UL 1741. The nondetection zone has been found negligible experimentally in [8], which is a system involving one cycle-controlled inverter that is free from phase-locked loop implementation. This method is an active method, but external signal injection is not required. An active method used in [9] can detect islanding in PMSG-based DGs (distributed generators) within 178 ms. Frequency changes implicitly during post islanding condition, whereas external signal is injected. In some adverse situations, the islanding is detected within 200 ms. A solar farm is present in the 6 bus test system used in [10]. IEC62116 criterion is applied to the measurements obtained from phasor measurement units to detect islanding as in [10]. This method is a communication-based method. The measurements and reporting standards are different in case of μPMUs, which are used in [11] and [12] for islanding detection in distribution systems. Both the methods in [11] and [12] are passive. P-type μPMU is used in [11]. The Fortescue transform helps compute phase angle sequence. The difference between positive absolute angle component and zero absolute angle components is used to initiate signal for accomplishing intelligent islanding. A

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quick and reliable method in [12] using kurtosis and random forest classifier can detect islanding in 20 ms.

El Khalil El-Arroudi et al. [13] have developed islanding detection technique based on threshold values of voltage, frequency, rate of change of frequency, and power. In [14] a ROCPAD islanding relay has been developed and islanding conditions are tested for different power mismatches. Negative sequence of voltage at point of common coupling as well as Parseval's theorem is applied for islanding detection in [15]. When the energy content of the signal exceeds a threshold value, islanding is confirmed. A new Fast Gauss-Newton Algorithm (FGNWA) has been developed in [16] for islanding detection. Gauss-Newton algorithm combined with approximated Hessian matrix generates FGNWA. A low-cost autoground system has been developed in [17]. It has a single installation point, but this method is unproven in the field and causes faults in the DGs.

Machine learning techniques such as support vector machine and ensemble tree classifier are used in [18] for islanding detection. The method in [19] can detect islanding for both inverter-based DG and synchronous DG. K-fold cross validation has been used for testing the accuracy of the algorithm. This validation produces biased results for low values of k. In [20], autoregressive coefficients of voltage and current have been used for islanding detection. The detection time is 50 ms, which is high to some extent. An islanding detection on real-time Distributed Energy Control Center microgrid has been experimented in [21]. This laboratory provides a unique facility at the Oak Ridge National Laboratory. The algorithm in [22] can detect islanding by connectivity checking. It is based on network topology and does not require data on the network parameters. The rate of change of voltage phase angle (ROCOVPA) has been incorporated in [23] for islanding detection for several case studies defined by the IEEE 1547 and UL 1741 standards. An adaptive ensemble classifier has been used in [24].

Adaptive decision mechanism is designed with this algorithm to adjust the decision time with events classification. Probability of islanding (PoI) [25] is estimated in aggregation with active, passive, and communication-based methods. If the central control for microgrid (CCMG) does not receive PoI, two supplementary process are performed to detect islanding in an alternative way. Using two methods during communication failure is not computationally efficient. Intelligent relay based on decision trees [26] has been reported to reduce nondetection zone boundaries, described by established methods. Helmholtz oscillator can detect islanding in near zero active power mismatch as testified in [27] in multiple DG based system. Modal components can be calculated from phasor data as mentioned in [28]. Islanding detection factor can be calculated from modal components. Despite the small detection time, nondetection zone has not been verified in this method.

Main Points

- Classification and description of islanding detection techniques.
- Discussion of several standards; for example, IEEE1547, UL1741, and IEEE929, related to islanding.
- Classifying the occurrence of islanding in different systems is important for selecting appropriate algorithms and techniques. This article presents the consequences of islanding on different systems. It also describes the consequences of solar distributed generators (DGs), wind DGs, and synchronous DGs in a distribution system islanding.
- Comparison of nondetection zone and advantages and disadvantages of various types of islanding detection algorithms.
- Conclusion and future scope of the topic based on the discussion and comparison of algorithms.

A real-time islanding detection method on Turkish power system has been implemented in [29]. This method can heal the power system on the basis of the severity index. A novel distributed energy resource-driven nondetection zone (D2NDZ) method has been proposed in [30]. D2NDZ formulas are initially recognized by experimental study, and then parameters are determined by optimization method. An adaptive neuro-fuzzy interface system for islanding detection has been validated by UL1741 standards in [31]. Gibbs phenomenon can be incorporated with RMS and THD for islanding detection as declared in [32]. Measurements obtained from µPMU are further processed by Fortescue transform to detect islanding [33]. In this method, the detection time is high.

Artificial neural network-based islanding detection has been presented in two studies [34, 35]. These two methods are moderately time consuming. A new event-based ellipsoidal estimation set [36] has been proposed for islanding detection in a 2-kW single-phase grid-connected power generation system. Event triggering can reduce the transmission frequency for saving the communication resources. Dual frequency based active islanding detection method described in [37] is also advantageous for grid impedance detection. The proposed hybrid islanding technology in [38] involves both the mean of absolute d-axis voltage variation (ADVV mean) and mean of absolute rate of change of d-axis voltage (AROCODV mean). The event detection is represented geometrically in [39] for islanding detection. Principal component analysis is used to reduce data dimension in this method. In the literature [40], several tendencies and future of islanding detection methods are prescribed. Role of micro-phasor measurement unit during uncertainties in power system are analyzed in [41]. Phase comparison–based islanding detection index has been proposed in [42]. The chance of a cyberattack has been reduced in [43] during islanding detection. The threshold values for islanding detection have been estimated experimentally in [44]. Discrete fractional Fourier transform has been implemented in [45] for fast detection of islanding. GOOSE-based passive islanding has been tested in hardware in loop in [46]. Islanding probability can be found out experimentally during missing communications as publicized in [47].

A variety of technologies for islanding detection is illustrated in Section 2. Comparisons of different islanding detection methods are given in Section 3. Section 4 concludes the article.

Description and Classification of Islanding Detection Techniques

In this section, the islanding has been visualized in a simple system, some important standards have been discussed before the detailed description, and comparison of islanding detection methods have been performed.

Occurrence of Islanding on Simple Systems

When the inverter is working in a grid-tied mode, its frequency is dominated by the grid frequency through a feedback controller. When island occurs, the power frequency of the inverter deviates from nominal value, and the voltage profile becomes unstable in nature. The controller is then arranged to make the inverter operative in a stable region. Some dual-mode inverters can operate in both grid-tied and off-grid condition. The changing of controller from grid-tied mode to islanded mode requires islanding detection. Islanding test setup consisting of an inverter, *RLC* load, and utility grid is shown in Figure 1. The solar panel supplies DC power to the inverter, and the inverter feeds AC supply to the local *RLC* load.

$P_L + jQ_L$ is the amount of power taken by the *RLC* load. Islanding occurs when $\Delta P + j\Delta Q$ is zero. Performance of islanding detection method can be evaluated by gradually equating $P_L + jQ_L$ and $P_{DG} + jQ_{DG}$ in a step-by-step manner. For visualizing the islanding situation in transmission system, the solar inverter setup and the controller can be replaced by generating station along with a step-up transformer as depicted in Figure 2. The mathematical interpretation is equivalent to the distribution system as mentioned before. Islanding detection time should be less if voltage and frequency deviation is more. [1] and [2] are followed for Figures 1 and 2, respectively.

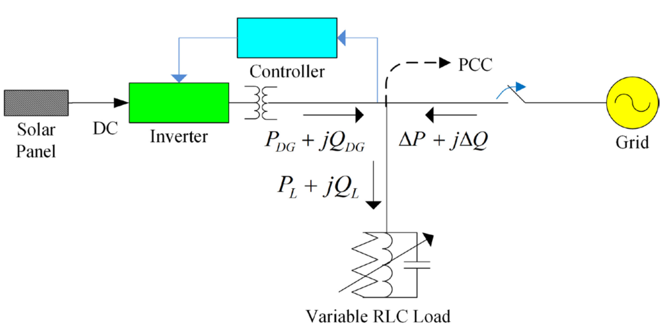

Figure 1. Schematic diagram of islanding study in a distribution system

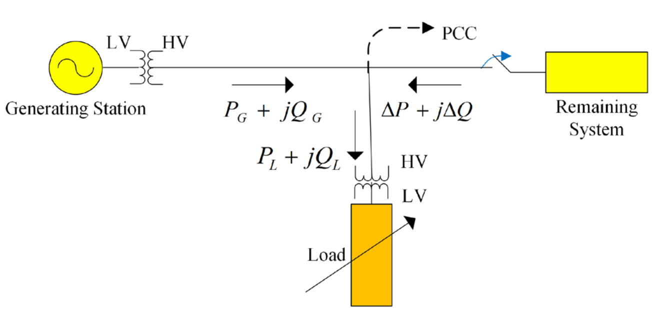

Figure 2. Schematic diagram of islanding study in a transmission system

$$(P_{DG} + jQ_{DG}) - (P_L + jQ_L) = \Delta P + j\Delta Q \quad [1]$$

$$(P_G + jQ_G) - (P_L + jQ_L) = \Delta P + j\Delta Q \quad [2]$$

Some more details can be incorporated for nondetection zone. It can be evaluated based on power mismatches. Let V_{mx}, V_{mn}, f_{mx}, f_{mn}, Q_f be maximum voltage, minimum voltage, maximum frequency, minimum frequency, and quality factor, respectively. The threshold power mismatches are obtained as [3] and [4].

$$\left(\frac{V}{V_{mx}}\right)^2 - 1 \le \frac{\Delta P}{P} \le \left(\frac{V}{V_{mn}}\right)^2 - 1 \quad [3]$$

$$Q_f\left(1 - \left(\frac{f}{f_{mn}}\right)^2\right) \le \frac{\Delta Q}{P} \le Q_f\left(1 - \left(\frac{f}{f_{mx}}\right)^2\right) \quad [4]$$

The values of R, L and C in Figure 1 can be so adjusted as to get zero power mismatch as mentioned below in [5], [6], [7], and [8].

$$R = \frac{V^2}{P_L} \quad [5]$$

$$L = \frac{V^2}{2\pi f Q_f P_L} \quad [6]$$

$$C = \frac{Q_f P_L}{2\pi f V^2} \quad [7]$$

$$f = \frac{1}{2\pi\sqrt{\frac{L}{C}}} \quad [8]$$

where P_L represents load power and f represents operating frequency.

Several Standards Related to Islanding Detection

There are several control strategies, standards, and islanding testing criteria. According to IEC 62116, the allowable voltage range is 0.85 to 1.15 of nominal voltage, and the frequency deviation is allowed up to ±1.5 Hz from nominal frequency. The voltage and frequency deviation for IEEE1547 and IEEE929 are the same for safe operation. The voltage range is 0.88–1.10 of nominal voltage, and frequency range is within 59.3–60.5 Hz for both of IEEE1547 and IEEE929.

It is mentioned in UL1741 standard that the load should be adjusted in such a way to make the DG supply 25%, 50%, 100%, and 125% of the rated active power. The reactive power is also adjusted by ±5% of rated active power.

Classification of Islanding Circumstances and Islanding Detection Methods

Islanding detection techniques can be broadly classified as active, passive, communication-based, and hybrid methods. The detailed classification is showed in Figure 3.

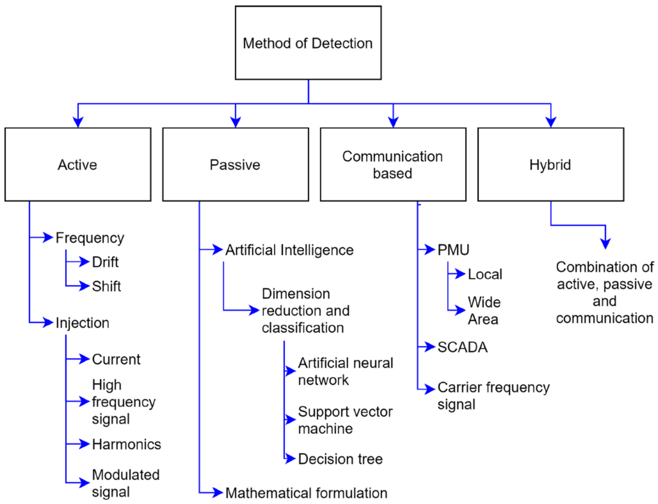

Figure 3. Classification of islanding detection techniques

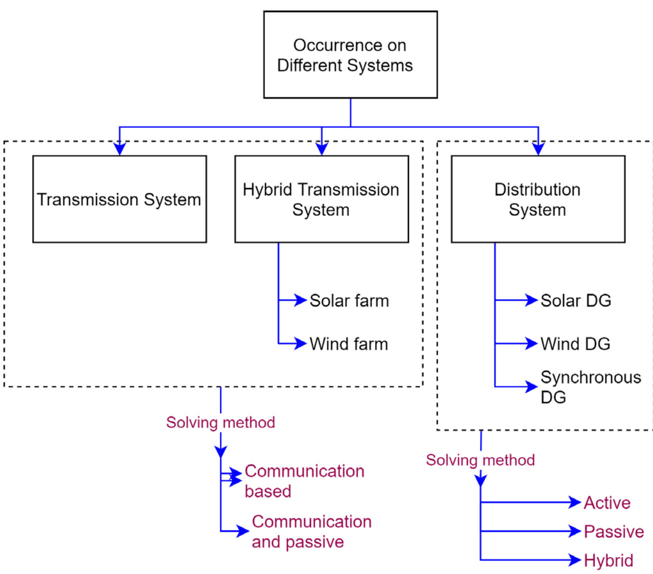

Figure 4. Classification of islanding based on occurrence of different systems

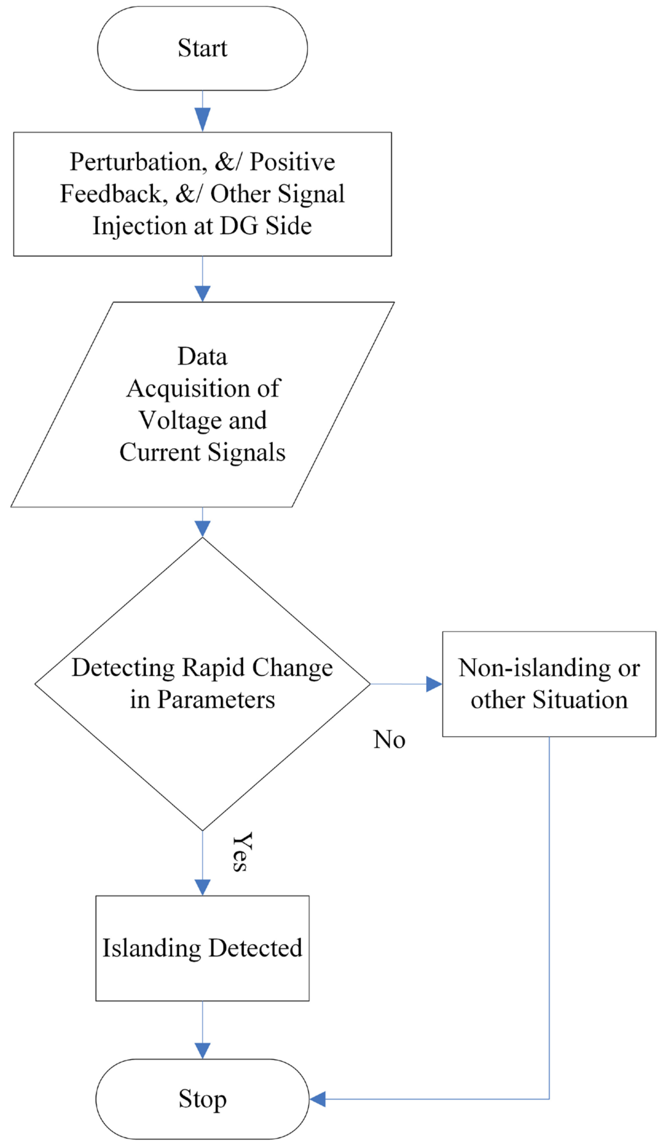

Figure 5. Active islanding detection

Islanding may occur in different systems that play an important role in choosing a detection method. The occurrence of islanding in different systems has been categorized in Figure 4

It is observed that the communication-based method is applicable to transmission related systems, and other methods are applicable to distribution systems. The descriptions of four classifications: active, passive, hybrid, and communication-based methods are discussed in this subsection.

A comprehensive active method flowchart is depicted in Figure 5.

According to Figure 5, rapid change in parameter is observed owing to signal injection in the islanding condition. Rapid change is unavoidable when DG power equals load power consumption. Therefore, the active method has no nondetection zone in zero mismatched condition. However, the nondetection may occur in some situation other than zero mismatched condition. In some advanced active methods, the nondetection zone is persuasively made zero in a hybrid mode.

The passive islanding detection is generalized in Figure 6. No external signals are injected, and only the measurements are analyzed. Nondetection zone is present to an accountable extent for passive methods. Nondetection occurs when $P_L + jQ_L$ is equal to $P_{DG} + jQ_{DG}$. However, this method does not affect the power quality.

Communication-based methods are described in Figures 7 and 8. As seen in these figures, the communication-based islanding detection is allocated into two different flowcharts. According to

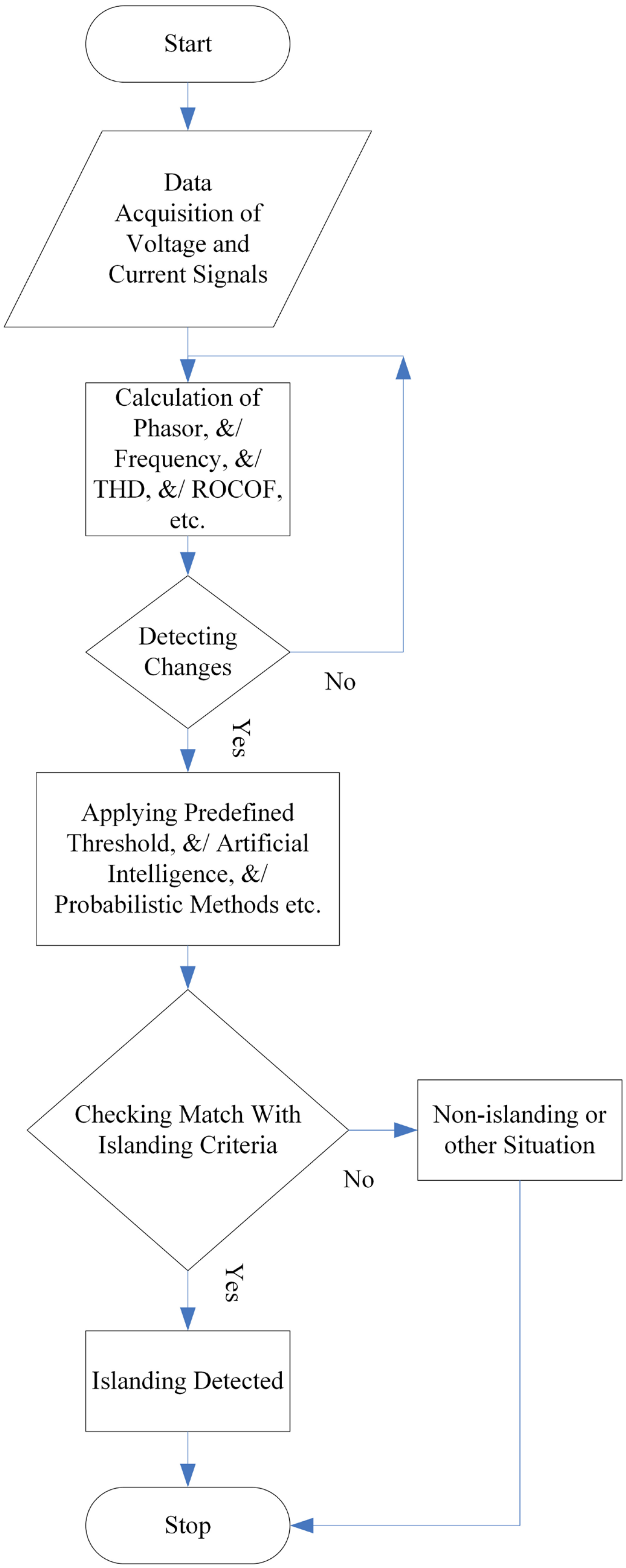

Figure 6. Passive islanding detection

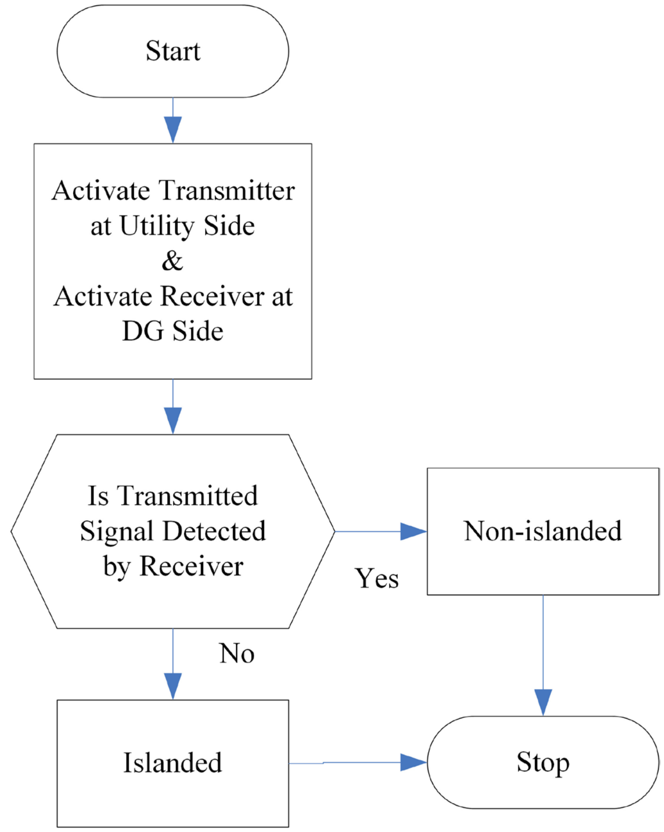

Figure 7. Radio/microwave/power line carrier/ signaling based islanding detection

Figure 7, carrier frequency signal is used to communicate between the utility and inverter sides. One transmitter is present in the utility, and several receivers are present with all the inverters. The transmitter and receiver pair helps detect the islanding condition. If the receiver does not obtain proper carrier frequency signal sent by the transmitter, islanding is confirmed. In phasor measurement [Figure 8], devices are placed in both the utility and DG sides. The difference in measurements between the two sides reflects islanding condition.

As seen in Figure 9, both passive and active criteria are applied successively. The limitations of both active and passive methods are compensated by the hybrid method in Figure 9. Nondetection zone created in the passive method is cleared by the active method, and the nondetection zone that would have been produced in active is already eliminated in the passive method.

Comparison of Different Algorithms

All the algorithms have some limitations. A nondetection zone is always present for each of the algorithms. Generally, passive methods fail in a region where load demand is equal to DG generation. If the phase angle of the load is zero, it will not create much phase shift during islanding; therefore, the use of phase-jump-method is limited to islanding detection in linear loads. Islanding detection using harmonics analysis is not effective for loads with strong low pass characteristics or having high quality

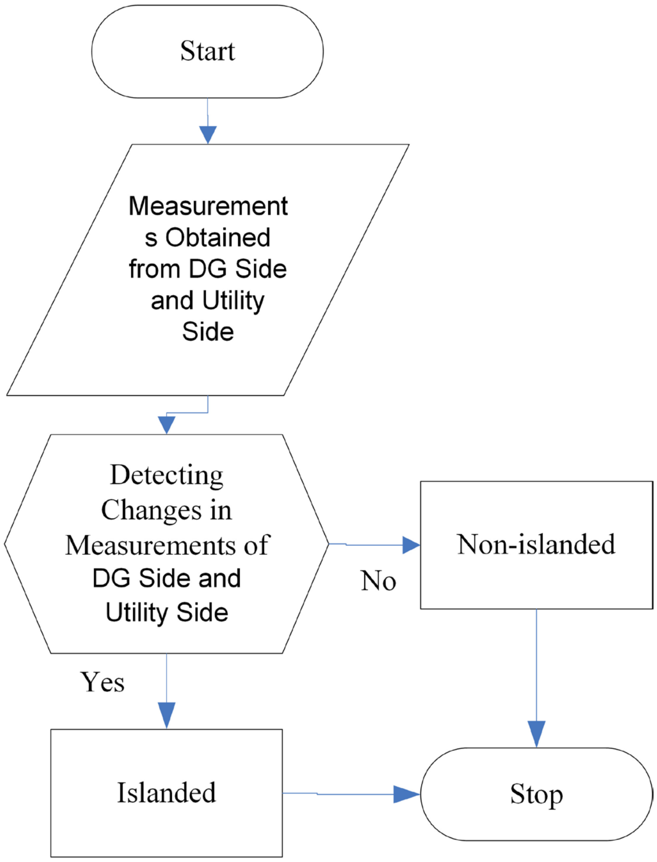

Figure 8. SCADA/synchrophasor based islanding detection

factor. For an electrically strong grid, the impedance of the generator is practically nonzero. Thus, an impedance threshold of small value is specified by the impedance measurement technique. The islanding detection criterion lies below this small threshold value. If local impedance is already less than the threshold, impedance-based islanding detection method is not applicable. For communication-based islanding detection using power line carrier communication, the load may produce a carrier signal similar to the signal produced during islanding condition. This may cause false islanding detection. Few aspects of active methods are described in Table 1.

Active frequency drift, Sandia frequency shift, and slip mode frequency shift are the earlier methods of active islanding detection. Currently, researchers are interested in more advanced methods, for example, pulsating signal injection, capacitor insertion, Q-V droop, d-axis disturbance injection, etc.

Several comparative analyses of passive methods are given by Table 2. Some threshold limits of electrical parameters shown in Table 2 were used earlier to detect islanding. However, in the present situation, the practice of several signal processing techniques, for example, wavelet transform, hyperbolic-s transform, and mathematical morphology, etc. are used to detect islanding conditions. These methods have proven useful for islanding detection accurately.

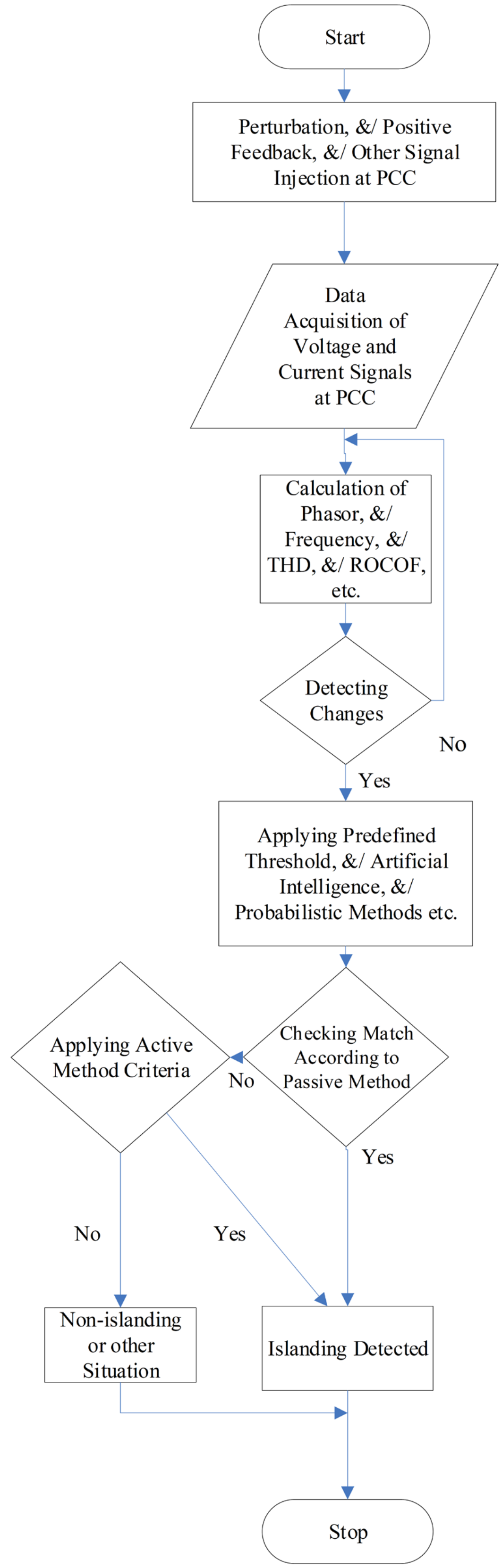

Figure 9. Hybrid islanding detection

Table 1. Comparison of active islanding detection algorithms

Algorithm	Advantage	NDZ	Disadvantage
Active frequency drift	• Easily implemented using microcontroller.	• NDZ is relatively large than other active methods. • NDZ depends on chopping fraction.	• Adverse effect on power quality. • Instability in positive feedback. • Current discontinuity may cause radio frequency interference.
Slip mode frequency shift	• Easy to implement. • Applicable to multi-inverter system.	• Small NDZ.	• Adverse effect on power quality. • Instability in positive feedback.
Sandia frequency shift	• Easy to implement • Compromise between power quality and islanding detection effectiveness.	• Small NDZ. • NDZ depends on gain value.	• Higher gain may cause transients, and lower gain causes large NDZ. • Instability in positive feedback.
Improved active frequency drift	• 30% less THD compared with AFD [36]. • Faster operation.	• Improved NDZ compared with AFD.	• More complicated than AFD • Instability if positive feedback is used.
Adaptive fuzzy Sandia frequency shift	• Gain is optimized to reduce both NDZ and transients.	• Smaller NDZ than in Sandia frequency shift.	• More complicated than Sandia frequency shift. • Instability in positive feedback.
Average absolute frequency deviation	• Detects stable islanding. • Do not involve system stability. • Power quality and power factor is improved by using small reference current.	• Small reference current may cause large NDZ.	• False islanding detection owing to frequency deviation other than islanding condition. • Rechecking must be done for islanding confirmation.
Impedance-based analysis of active frequency drift	• Can detect islanding even when power supplied by inverter is equal to power consumed by load (impedance insertion is used in this condition).	• Small NDZ	• Similar disadvantage as active frequency drift.
Real power shift	• Clear discrimination between islanding and nonislanding • Simple algorithm, easy for implementation.	• Small NDZ.	• Degrades power quality. • Less stable operation.
Negative sequence current/power injection	• Faster operation • Applicable to parallel DG and double DG system.	• NDZ can be reduced using RLC space based on a relatively minor modification in the control algorithm.	• Degrades power quality. • Less stable operation. • Instability owing to positive feedback. • Detection time doubles if the load parameters are in the NDZ space.
Capacitor insertion	• Provides reactive power support. • Prevent islanding for small duration.	• Small NDZ.	• Economically not feasible. • Difficulty in determining the part of a power system responsible of installing capacitor for a multi-DG system.
High frequency signal injection	• Islanding is detected in a few milliseconds. • Negligible adverse effect owing to injected high frequency voltage. • 0.3% line voltage is required for islanding detection causing 0.11% THD.	• Small NDZ.	• Degrades power quality. • Less stable operation. • Unstable operation.
Controlled inverter	• Improves stability and islanding detection performance. • Applicable for weak grids.	• NDZ present.	• Stability depends on the design of integral controller.
Reactive power control/ voltage regulation	• Applicable to high penetration PV unit. • Small effect on power quality. • No interference in multi-PV system.	• Small NDZ depending upon proportional controller gain.	• Stability depends on the design of integral controller.

d-axis disturbance signal injection	• Minimum effect on power quality. • Reliable operation. • Wavelet fuzzy neural network used instead of PI controller.	• Quasi-zero NDZ.	• Similar disadvantage as wavelet and fuzzy logic.
Frequency fuzzy positive feedback	• Positive feedback is restricted depending upon system stability. • Decreased NDZ compared with other positive feedback method.	• Small NDZ.	• Similar disadvantage as using fuzzy logic. • Positive feedback may reduce stability.
Q-V droop plus correlation	• THD is between 0.01% and 0.38%. • Better than slip mode frequency shift, active frequency drift, and reactive power control.	• NDZ is determined by the region under frequency threshold.	• Unstable operation owing to positive feedback. • Similar disadvantage as correlation. • Islanding detection time is moderate (123.5–216.9 ms).
Transient stiffness measure	• Applicable to multi-DG system, avoids spectrum overlapping. • Detecting islanding for micro-grids with droop control. • Perturbations injected by the proposed method have no effect on the stability.	• Negligible NDZ	• None.
Pulsating high frequency signal injection	• Can handle linear and nonlinear loads. • Multi-DG operation is possible.	• Not described.	• Unstable operation and power quality issue.

Table 2. Comparison of passive islanding detection algorithms

Algorithm	Advantage	NDZ	Disadvantage
Kalman filter	• Able to take into account quantities that are partially or completely neglected in other techniques. • Detection within 45 ms.	• NDZ present.	• Complicated procedure. • Can only be used for linear state transition and Gaussian model.
Under/over voltage Voltage vector shift Rate of change of voltage phase angle Under/over frequency	• Simple to implement • Low-cost active method	• ND occurs when inverter power matches load consumed.	• Under/over voltage may be caused owing to nonislanding condition. • Large NDZ. • Detection time is higher. • Load having zero phase angle may not produce phase angle change in islanding condition.
Fifth harmonic	• Satisfies IEEE Standard 1547. • Eliminates NDZ.	• Negligible NDZ in normal condition.	• Similar fifth harmonic can be generated from noise or other nonislanding criteria.
Switching frequency from inverter	• Can detect islanding in 20ms. • Can be applied to multi-DG system.	• Zero NDZ.	• None
Wavelet	• Better than Goertzel or discrete Fourier transform based algorithm. • Fast algorithm.	• NDZ present.	• Can be improved using other algorithms.
Data mining	• Eliminate false detection. • Superior decision making.	• Medium NDZ.	• Computational effect is high during starting
Bayesian	• Faster operation • Accuracy up to 100%	• Depends upon Bayesian classifier.	• None
Duffing oscillator	• Applicable when noise to signal ratio is high. • Can detect weak signals.	• Small NDZ. • NDZ of the proposed method is subject to the frequency deviation rather than the load quality factor.	• None

Table 2. Comparison of passive islanding detection algorithms (Continue)

Algorithm	Advantage	NDZ	Disadvantage
Machine learning and wavelet design	• Wavelet parameters are determined using Procrustes analysis. • Better than simple wavelet transform. • Machine learning helps in automatic classifier.	• NDZ is smaller than in wavelet algorithm.	• None
Reference impedance based or frequency dependent impedance change	• Enhancement to the UF/OF method. • Considering harmonic frequencies other than fundamental. • Standard 1547-2003 satisfied.	• Reduced NDZ compared with UF/OF.	• None.
Phase space technique	• Stabilize the islanded part of the system with minimum load curtailment. • Better than wavelet.	• NDZ present.	• Slower procedure.
Thevenin-like model	• High sensitivity and reliability, does not require expert tuning. • Can detect islanding when DG balances loads. • Detection time is 100–200 ms.	• Null NDZ.	• Linear representation is not helpful in all cases.
Islanding search sequence	• Impact on normalized active and reactive power is less than 1%. • Optimized procedure of islanding detection within 250 ms (including the relay/contactor opening time, voltage collapse within safe limit). • Overall system perturbation is very less (1%).	• NDZ present	• None. • Islanding detection time is high (250 ms).
Hyperbolic s-transform Time to time transform Mathematical morphology	• Islanding detection in 22 ms, 22 ms, and 25 ms for Hyperbolic, Time to time and Mathematical method respectively. • Applicable for noisy conditions. • Sag, swell, flicker, inrush, and oscillation can be detected with good accuracy. • Applicable to multi-DG system.	• Less NDZ.	• None.
Dynamic estimator	• Superior performance for high quality factor. • Less than four cycles needed to determine islanding.	• Small NDZ.	• None.
Oscillation frequency	• Islanding detected in 40 ms. • Better than ROCOF method.	• NDZ less than 1.6% for rated DG power.	• Calculation of damping coefficient is omitted resulting in inaccuracy.

NDZ: nondetection zone, AFD: active frequency drift, THD: total harmonic distortion

Some important aspects of communication-based methods are discussed in Table 3. Principal component analysis becomes unavoidable to reduce the dimensionality when applying phasor measurement units. These reduced dimensional features are used for islanding detection. GPS based communication is also considered for synchrophasor technology. Synchrophasor based islanding detection is computationally lengthy and cost effective. However, these methods are reliable, modern, and fast compared with the other communication-based methods.

Future Scope

A lot of new studies can be conducted on the basis of current literature on islanding detection techniques as mentioned below:

- Based on the severity of the islanding, a ranking can be proposed for a particular system. The ranking can help the controller to take priority-based actions.
- All transmission islandings are not hazardous, and it is important to classify hazardous and nonhazardous islanding.

Table 3. Comparison of communication-based islanding detection algorithms

Algorithm	Advantage	NDZ	Disadvantage
Radio or microwave	• No power quality issue.	• Normal operating state has no NDZ.	• Affected by other radio frequency or microwave signals. • Expensive.
Power line signaling	• Can be used for data as well as sending power.	• Small NDZ.	• High carrier frequency involved for data communications and the sub-optimal design of power systems is required when transporting high frequency signals.
Power line carrier	• Does not affect power quality. • Does not involve transient condition. • Co-operate to increase ride through capability.	• NDZ does not exist in normal condition.	• Very expensive and uncommon.
Fiberoptic	• Operated in long range. • Low loss of signal. • Large data carrying capacity. • No electromagnetic radiation.	• No NDZ present.	• The transmitter and receiver for fiberoptics are very expensive. • Cannot carry electrical signal, thus backup required for control action.
Leased line	• Not affected by external noise. • No power quality issue. • Less expensive. • Reliable operation.	• No NDZ present.	• Delay is considerable for slow connection.
Transfer trip scheme	• No power quality issue.	• NDZ is present because of weak in-feed condition.	• Islanding detection speed depends on circuit breaker and re-closer operating time. • Weak in-feed condition has adverse effect. • Loss of communication is considerable.
SCADA	• Eliminates islanding condition. • Takes control over islanding situation.	• No NDZ present.	• Not synchronized. • Costly procedure.
Phasor measurement unit	• Fast, accurate, modern, and synchronized technique. • Can be applied to wide area islanding detection. • Loss of communication is rare.	• No NDZ present.	• Expensive • Principal component analysis becomes mandatory to reduce dimensionality.

NDZ: nondetection zone

Nonhazardous islandings are really necessary in certain situations to maintain stability in the islands.

- Universal controller, which can operate in both grid-tie and off-grid modes, has been developed in some studies. The controller does not require any islanding detection technique for the operation. Future research can be conducted related to the universal controller for improvement of smart microgrid expertise.
- Probabilistic approaches are highly appreciable for manipulation of islanding scenarios in some adverse situations, for example, cyberattack, lost communication, missing data, etc.

Conclusion

We have discussed a total of 18 active islanding detection techniques. All the methods are applied to distribution systems only. The nondetection zone is negligible. The power quality issue is unavoidable in active islanding detection as mentioned in the literature. Notably, 22 kinds of passive methods have been elaborated. These methods are applied to both transmission and distribution systems. No power quality issue has been reported in the literature for passive methods. These methods are faster than the active methods, but nondetection zone where islanding cannot be detected is more. Eight types of communication-based method have been discussed in this article. These methods are applicable to large transmission and distribution systems for accurate islanding detection. Communication-based methods are costlier than passive methods.

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REVIEW

The Development of Lightning Protection and Grounding Systems: A Survey

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ABSTRACT

The development in the industry and the increasing demand for electrical energy has made it necessary to provide electrical energy safely and continuously. A well-designed and implemented lightning protection and grounding system will protect users and equipment against malfunctions in electrical installations. Therefore, lightning protection and grounding systems have become an essential topic in recent years, and many studies have been conducted in the literature based on this. In this study, we reviewed more than 45 studies on this subject conducted in the past five years.

Keywords: Lightning protection, grounding systems, power systems, artificial intelligence-based methods

Introduction

Electric energy has become an indispensable part of our lives. Especially for the growing and developing industry, electrical energy is even more vital. Ensuring continuity of production, safety of people and animals, and reducing costs depend on the correct and reliable installation of electrical systems. Systems that are not designed correctly can harm humans or animals. In addition, repairs or equipment changes can lead to serious costs or interruption in production. Therefore, grounding and lightning protection systems have been a topic of many studies in recent years. Lightning discharge currents are dissipated safely in the grounding system by lightning protection systems. Lightning protection systems protect the electrical and mechanical components in the buildings against lightning discharge currents. Lightning can cause serious damage to transmission and distribution lines, wind turbines, or buildings. Lightning is one of the most frequent events causing transmission line outages. Estimating lightning outages before they occur is an effective method that can be used to prevent negative consequences. Nowadays, artificial intelligence-based applications using lightning and lightning outage data recorded in power systems are becoming widespread to estimate lightning outages.

Grounding is defined as the joining of inactive sections and zero conductors and the sections connected to them in a conductive way with the help of an electrode. In other words, earthing, which ensures the prevention of leakage that may occur in electronic devices without causing damage, is the process of transmitting electrical currents to the ground. This ensures the protection of life and property in the event of a possible electrical leak. Damages are prevented both in the structure of the buildings and in human health.

In this study, we reviewed recent studies on lightning protection and grounding systems and also artificial intelligence-based lightning protection and grounding systems. Thus, it is aimed to provide a broad perspective on these subjects to the researchers.

Literature Review

The articles examined are presented under the following titles: Lightning Protection, Grounding Systems, and Artificial Intelligence-Based Lightning Protection and/or Grounding Systems. Recently, artificial intelligence-based studies have become quite common and important. Therefore, artificial intelligence-based lightning protection and grounding systems were examined under a different title. The method, algorithms, and the software used in articles examined in this survey are summarized in Figure 1.

Lightning Protection

Today, the use of renewable energy sources has increased signifi-

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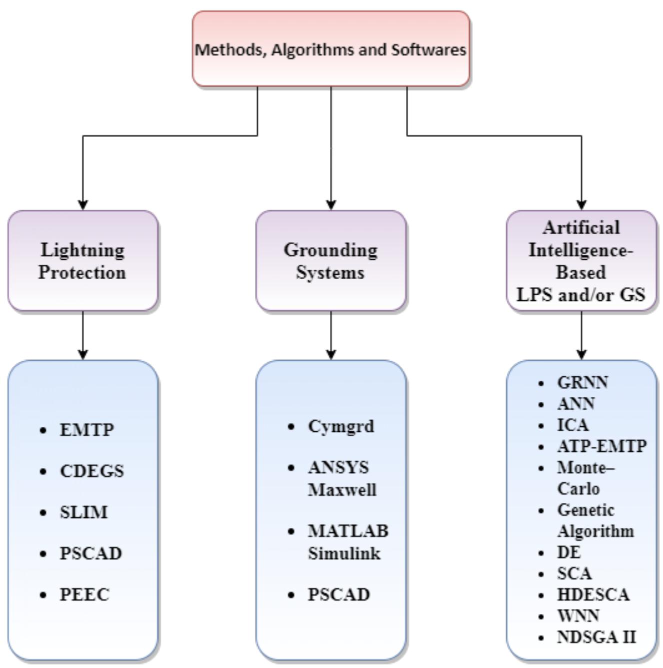

Figure 1. Methods, algorithms, and software used in the articles

cantly, and the number of solar and wind power plants installed worldwide has also increased. These power plants are generally built on large areas with high altitudes. In wind farms, both the areas where they are installed, and the special structure of the turbines make them more vulnerable to lightning strikes. Therefore, the location of the wind farm, influence of the local terrain, and seasonal variation of lightning play a critical role for conducting risk assessment [1].

The distance between the turbines is also important for lightning protection in wind farms. In the study conducted by Zhang et al. [2], the distance between two wind turbines required for protection against lightning is calculated on the basis of the new electrical geometric model of wind turbine blade. The results showed that for a typical 1.5 MW wind turbine, the layout distance in the vertical direction should be 4-6 times the length of the blade.

Lightning strikes can seriously damage wind turbines. This causes high cost and time loss to replace or repair components damaged by lightning strikes [3]. In addition, lightning strikes can be a serious danger for operators. Therefore, lightning protection systems are essential and vital to protect both the turbines components and human operators. Damages caused by lightning strikes on a wind turbine blade can be classified as delamination, deboning, tip detachment, and shell detachment. Garolera et al. [4] investigated 304 lightning damages on wind turbine blades in different wind farms in USA, and it was observed that the most frequent lightning damage was delamination.

Receptor behaviors under the lightning strikes were experimentally investigated through various experimental configurations. In the study conducted by Guo et al. [5] the experiments indicated that although negative lightning strikes are much more common than positive lightning strikes in nature, positive lightning strikes have higher peak currents than negative lightning strikes. Therefore their damage may be greater and more severe.

A lightning protection system is critical in the design and installation of a wind farm. Deshagoni et al. [6] used CDEGS software package to find the factors that determine the effectiveness of a wind turbine generator. The results showed that grounding system is crucial for wind turbine lightning protection systems. Moreover, it has been observed that low resistivity soil sites and proper design of soil stratification and earth electrodes can improve the effectiveness of the grounding system. An experimental study that was conducted using a small-scale wind turbine has also shown that a grounding system is essential for design of lightning protection system of the wind turbine [7].

Overvoltage can damage underground cables sometimes when direct lightning strikes the wind turbine. Sekioka et al. [8] used electromagnetic transients program (EMTP) for lightning surge analysis when the direct lightning struck the generation system. As a result, it has been revealed that the cable model plays a critical role for accurate surge analysis. In addition, simulation results show that the lightning overvoltage depends on the grounding condition of the cable sheath.

In the study conducted by Long et al. [9] self-consistent leader inception and propagation model is used for analyzing the effect of the rotation angle of the blade and the wind and the prospective return stroke peak current on the location of lightning strikes. The results show that only when the blade of a wind turbine rotates sufficiently from its initial position until the start of the dart leader approach, a new strike point is created.

Lightning strikes are also a serious problem for solar PV systems. When lightning strikes a solar PV system, transient voltage and current appears. Zaini et al. [10] simulated the effects of lightning strikes on a solar PV system by using PSCAD. The results indicated that a transient current will appear at the nearest point to the lightning strike. Zhang et al. [11] proposed a PEEC method for analyzing lightning transients in PV systems. Further, an experiment was conducted for the confirmation of the proposed method. Although the induced voltage was not significantly affected by soil resistivity, the results of the study revealed that the voltage between the DC cable and ground was significantly affected by the soil resistivity.

It is crucial to protect the transmission and distribution lines against lightning to provide consumers with quality and continuous electrical energy. To improve the lighting protection level, arrester and grounding line can be used for distribution lines [12]. A distribution feeder can be affected by lightning in two ways. First, the lightning can have a direct effect on overhead distribution lines. Second, lightning strikes the ground and as a result of this an overvoltage is induced in the insulator strings [13].

In the study conducted by Banjanin [14] special lightning protection methods were examined comparatively, and their efficiencies was calculated and compared for reduction to the overhead lines back-flashover rate. The EMTP/alternative transients program (EMTP-ATP) software was used for creating system equivalent circuits. It has been demonstrated that using underbuilt wires can provide a highly efficient lightning protection system.

Gu et al. [15] conducted the risk assessment of an ultrahigh voltage DC line as an example to improve the existing electrogeometric model. The back propagation neural network algorithm was applied to integrate three methods of warning using radar echoes, atmospheric electric fields, and lightning detection data to develop the warning model.

Ding et al. [16] established Sunan unified power flow controller (UPFC) using the EMTP-ATP to analyze the lightning invasion wave. In addition, a double exponential wave was used to simulate the waveform of lightning current. Simulation results suggested that the arrangement of the arrester has an essential role in limiting the lightning overvoltage level in UPFC.

Resende and Lopes used [17] , the EMTP-RV software to examine the transient behavior of the pole-mounted distribution transformers (DT). The results showed that installing a surge protection device not only on the medium voltage (MV) side of the transformer but also on the low voltage (LV) side is necessary for full protection of the pole-mounted DT.

In the study conducted by Zhang et al. [18] numerical simulation was used to analyze the relationship between the lightning protection effect of ground resistance and overhead ground wire, lightning strike position, insulator type, and tower type for the 10 kV distribution line. From the results, it was observed that the tower type, ground resistance, and insulator type had significant effects on lightning protection.

Grounding Systems

Implementing an efficient grounding system is not an easy task. Good planning and design require quality equipment and experienced practitioners. The grounding system is not expensive compared with the entire electrical facility, but it is an investment for the future of the facility. Grounding systems protect humans, buildings, and equipment from overvoltage, fire, and electrical leakage from metal surfaces.

To design an economical and reliable grounding system, the soil resistance of the site must be accurately measured. The Wenner method is frequently used in the literature to measure soil resistance. In the study conducted by Salam et al. [19] soil resistivity of two different sites (one with wet soil and one with dry soil) near the electrical substation were measured with the Wenner four-pole equal method, and the accuracy of the measurements was checked by taking the measurements and calculations into account with the Cymgrd simulation software. As a result, simulation results were found to be very close to the measurements.

There are many methods recently used in the literature to improve grounding performance. If the soil resistance value is unacceptable, methods such as salting treatment, chemical treatment, and vertical rods can be used to reduce the soil resistance [20]. Faudzi et al. [21] reduced the ground electrode resistance by using palm oil fuel ash as the backfill, and improvements in grounding performance exceeding 90% were achieved. Myint et al. [22] demonstrated that earthing resistance value could be changed with changing the electrode diameter and length and variation of the spacing of electrodes on earthing resistance.

Gonçalves et al. [23] presented two electrical models to simulate the responses of the grounding system to current impulses with capacitive or inductive characteristics. For the evaluation of the models, experimental tests were conducted in two different grounding systems. It was revealed that the proposed model had advantages such as ease of circuit implementation and parameter calculation.

The major role of wind turbines grounding system is reducing the overvoltage, thus preventing the damage caused by lightning. Grounding system of low impedance provides a suitable ground termination to limit dangerous overvoltage [24].

Wind turbine grounding systems generally show capacitive behavior when frequency-dependent soil parameters are considered [25]. In the study conducted by Sunjerga et al. [26] the impedance of the interconnected wind turbine grounding system was investigated using numerical simulation in which frequency-dependent soil parameters were considered. As a result, it was observed that when the conductivity of the soil was poor, additional horizontal wires and the interconnection of the wind turbine grounding systems can help keep the impedance within the recommended values. Similar results were obtained from analysis in the study conducted by Sunjerga et al. [27].

Alipio et al. [28] evaluated the relationship between the lightning response of the wind turbine grounding systems and the frequency dependence of the ground electrical parameters It was observed that the frequency dependence effect decreases the impulse impedance and the grounding potential rise. With the widespread use of offshore wind turbines worldwide, many studies on grounding systems for offshore turbines have been conducted [29-31]. Guo et al. [32] proposed topologies and strategies that could be used in grounding fault clearance in series connection based offshore wind farms were proposed. The experiments and simulations revealed that these strategies and topologies were practicable for this purpose.

Zhu et al. [33] examined a four-plate capacitive power transfer system experimentally and theoretically with different grounding connections. The system output performance and electric field distribution of the proposed system with different grounding connections were analyzed using MATLAB Simulink and ANSYS Maxwell. The result showed that when one pair of the coupled transmitter and receiver plates was grounded, some improvement was achieved. This type of grounding connection had a minimum effect on power transfer and also achieved the lowest leakage electric field and the highest voltage gain.

Djamel et al. [34] developed a model to calculate the transient behavior of the grounding systems when a lightning struck the power system. The results showed that the electrical properties of the soil, the lightning current intensity, and the geometry of the ground electrode significantly affected the impulse performance of the grounding systems.

In the study conducted by Rizk et al. performance of the thermal power plant grounding system was investigated when lightning strikes a nearby transmission tower. The thermal power plants are typically constructed close to the water for cooling process; therefore, in the study, impact of the nearby sea was considered. The results revealed that the sea had considerable impact on the propagation of electromagnetic fields through the grounding system and the distribution of the ground potential rise on the grounding system owing to its high conductivity.

Jayamaha et al. [36] evaluated the ground fault characteristics of DC micro grids using PSCAD/EMTDC under different grounding configurations. Analyses have shown that the safe operation of DC micro grids depends on the proper selection of ground fault detection scheme and the grounding configuration.

Trifunovic and Kostic [37] aimed to calculate grounding resistance of the grounding system used in typical 110 kV transmission line towers. They used a method based on the finite element method modeling and proposed that as this method was general, it could be applied to any grounding system.

Niquepa et al. [38] presented modeling and simulation of an underground mining power system with a high resistance ground. Distributed capacitance of conductors was taken into account. It has been noted that for a well-designed high resistance grounding method, the distributed capacitance of the entire system should be taken into account.

Artificial Intelligence-Based Lightning Protection and/or Grounding Systems

Studies are ongoing to develop lightning protection systems to prevent line outages and ensure safe and quality power transmission. However, to prevent lightning outages, besides a well-designed lightning protection system, the operation mode needs to be adjusted beforehand. This is possible by predicting lightning outages. Grounding systems provide protection against fault currents arising from situations such as lightning in electrical systems. In recent years, engineers have to estimate the behavior of grounding systems; and therefore, multiple studies on the same have been conducted in the literature.

In the study conducted by Aslani et al. [39] an automated approach to numerical analysis is presented to measure the number of direct lightning strikes at high towers. The lightning leader progression for all possible lightning current values and for all lightning leader tip positions in the space above the tower was performed using the conventional numeric method.
Sarajcev et al. [40] proposed a novel approach that used a combination of statistical lightning protection systems efficiency and genetic algorithm (GA) in designing techno–economically optimal external lightning protection systems of open-air substations. A large number of lightning strikes were simulated by means of the Monte–Carlo method. In addition, GA was employed to design the lightning protection systems for optimal design of air termination. According to the results, GA has been successfully used to optimize station protection designs.

Xie et al. [41] analyzed data from a power company's operation and management system for general regression neural networks (GRNN) input parameters, and then GRNN was built to perform lightning outage prediction. Comparison with back propagation and radial basis function neural networks was made to validate the effectiveness of the proposed method. According to the simulation results, the proposed method provided better prediction performance. Ullah et al. [42] proposed object detection using artificial neural network (ANN) to protect the buildings from the lightning strikes. The ANN was trained by different input, output, and hidden layer. As a result, different objects have been successfully identified for the lightning strike configuration using this method.

In the study conducted by Graditi et al. [43] the non-dominated sorting GA II was used to solve an optimization problem, which concerned the optimal reconfiguration of automated distribution networks that contain different grounded HV/MV transformers and also included safety issues among the objectives.

In grounding system behavior, two sections are important: soil ionization and inductive behavior. Gholami Farkoush et al. [44] investigated lightning effect on the grounding body by focusing on the inductive behavior of the grounding grid. A grounding simulation was designed in ATP-EMTP under lightning strike in normal computation. GA was proposed to a system for the optimization of the grounding grids. Gholami Farkoush et al. [45] analyzed and optimized the touch and step voltages in a power grid by using similar methods.

Gabr et al. [46] proposed GA to control the cost of grounding grid under the same security limitations. The proposed method was used to design the substation grounding grid of the "El Qasr" power plant. Moreover, CYMGRD software was used to simulate the design.

Sengar and Chandrasekaran [47], aimed to reduce the total cost and limit the value of the safety parameters to obtain the most suitable grounding system. For this purpose, sine-cosine algorithm, differential evolution, and hybrid sine-cosine algorithm with differential evolution algorithm (HDESCA) were used, and their effectiveness was evaluated in the design. The results indicated that the design based on HDESCA technique provided minimum safety parameters and less cost compared with the others.

Classification of the articles by years			
	Lightning Protection	Grounding Systems	Artificial Intelligence-Based LPS and/or GS
2016	4,10	34,37	43,46,48
2017	2,9,17	19,28	
2018	1,3,5,8,13,14	20,24,26,29,30,31,36,38	40,44
2019	6,7,11,12,15,16,18	23,25,27,35	39,41,42,45,47
2020		21,22,32,33	

Figure 2. Classification of the articles by years

Androvitsaneas et al. [48] developed a model to predict the behavior of grounding systems using wavelet neural network (WNN). For the training of the developed WNN, measurements of rainfall height and soil resistivity obtained from a field were used. The results show that the developed WNN was successful in predicting ground resistance for all rods.

Discussion

In this article, the recent studies on lightning protection and grounding systems were examined and the importance of this issue, which has increased in recent years, was reiterated. In addition, it has been observed that there is a focus on artificial intelligence-based studies leading to an improvement in this field. All reviewed articles are summarized by years in Figure 2.

Conclusion

The importance of lightning protection and grounding systems is increasing in many different areas with increasing focus in research on this subject as evidenced by literature review. With the incessant increase in power systems capacity and voltage grade, the proper design of lightning protection and grounding systems becomes more and more essential. Many different methods are used for the design and optimization of grounding and lightning protection systems. For instance, programs such as ATP-EMTP, PSCAD, and MATLAB are frequently used for simulation and analysis in recent studies. In addition, successful development of artificial intelligence-based algorithms has enabled these algorithms to be used in studies on lightning protection and grounding systems. In addition to the methods currently used, future studies should focus on artificial intelligence-based algorithms, which are relatively less in the literature and are available for development.

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