Long- and Short-Term Comparative Analysis of Renewable Energy Sources

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Abstract: Network working conditions are influenced noticeably by the connection of renewable energy sources to distribution networks. This becomes more and more important due to the increase in renewable energy source penetration over the last few years. This in turn can lead to a mass effect. As a result, the classical open network model with simple unidirectional direction of energy flow has been replaced with an active model that includes many local energy sources. This paper deals with the analysis of long- and short-term changes in power and energy generated by three types of renewable energy sources with similar rated power and which operate in the same region (i.e., located no more than tens of kilometers away). The obtained results can be a starting point for a broader evaluation of the influence of renewable energy sources on power quality in power systems, which can be both positive (supply reliability) and negative (voltage fluctuations and higher harmonics in current and voltage waveforms). It is important not only to correctly place but also to assure the diversity of such sources as it has been confirmed by the source variability coefficient. The long-term analysis allows us also to estimate the annual repeatability of energy production and, furthermore, the profitability of investment in renewable sources in a given region.

Keywords: harmonic distortion; power quality; renewable energy sources

1. Introduction

Environmentalists and politicians are now more willing to change energy policies. The use of limited natural resources such as hard and brown coal, petroleum or natural gas, is increasingly being replaced by the rapid development of end-use energy production using renewable sources, first of all hydropower (23.7% share in energy consumption in 2018 versus 17.3% in 2000), wind (6.6% vs. 0.2%) and solar (2.6% vs. 0.007%) [1]. Although this change started a few years ago and is rapidly advancing, one has to keep in mind that it also results in a number of potential problems which will escalate alongside the number of installed renewably energy sources [2]. This paper helps to identify one of these problems, i.e., the lack of continuous supply of energy, due to external conditions. One of the targets of the European Union for 2020 is to achieve 20% of its gross final energy consumption from renewable energy sources (RES) [3], but it is estimated that by 2050 RES will have the highest share in global primary energy consumption—see Figures 1 and 2. As a consequence, the power network models must reflect rather distributed sources and consumers who can become producers (prosumers) instead of models assuming simple unidirectional energy flow which dominated as recently as in the beginning of this century. Such a change can have both a positive and a negative influence on the network and end-users, especially in the field of power quality.
Quality of electrical supply is defined by the power quality and reliability, i.e., continuity of supply. Some indices describing voltage and current waveforms have been established in norms, e.g., EN 50160 [5], in order to measure power quality. Among the most often used indices there is the Total Harmonic Distortion (THD) coefficient, which can be calculated for current (THDi) and voltage (THDu) waveforms. The coefficient is dimensionless and defined as the ratio of the RMS value of a set of higher harmonics present in a signal to the RMS value of the fundamental harmonic:

\[
THDi = \sqrt{\sum_{k=2}^{n} I_k^2} / I_1
\]

\[
THDu = \sqrt{\sum_{k=2}^{n} U_k^2} / U_1
\]

where: \( I_k/U_k \) is the RMS value of current/voltage of the \( k \)-th harmonic, \( k = 1,2, \ldots, n \), and \( k = 1 \) means the fundamental frequency.

The 50160 standard [5] sets the maximum level of the voltage THD coefficient to 8%. It also defines allowable supply voltage variations and rapid voltage changes. Supply voltage variations
under normal operating conditions excluding the periods with interruptions should not exceed ±10% of the declared voltage for at least 95% of the average 10-min values over the weekly measurement period. Rapid voltage changes for medium voltage generally do not exceed 4% of nominal voltage but changes of up to 6% with a short duration of the sustained level might occasionally occur some times per day under some circumstances.

In recent times, one can observe a rising concern about power quality degradation caused by an increasing number of renewable energy sources connected to the power system and the cumulation of their negative influence.

As the renewable energy sources based on media (other than water) have been intensively developed for about 30 years, the number of relevant articles published in this time is very broad. They concern many specific problems and usually are devoted to one or two types of renewable energy sources. Power quality problems generated by such sources have been addressed in [6–10]. The role of renewable energy sources in evaluating the technical and economic efficiency of power quality without distinguishing between specific RES types has been presented by Ghiasi et al. in [11]. It includes analysis of the technical and economic implementation of power quality changes considering the effects of renewable energy sources on power systems. Power quality analysis of renewable energy sources, which include wind turbines, grid-connected photovoltaic (PV) and fuel cell power generation units, has been presented by Farhoodnea et al. in [12]. The effects of the RES technologies on system performances were investigated for various penetration levels and at different loading and weather conditions. Simulation results presented in [12] indicated that severe power quality problems such as voltage drop, frequency and voltage fluctuations, harmonic distortion and power factor reduction can occur. The impact of wind turbines and photovoltaic systems on network operation and power quality (harmonics and voltage fluctuations) have been analyzed on the base of case study by Golovanov et al. in [13]. The correlation between the generated power and the main power quality indices has been highlighted.

The majority of papers on power quality of renewable energy sources concern photovoltaic systems. These articles are mainly devoted to solutions that integrate PV systems with devices which enable reactive power compensation and higher harmonic filtering [14–19] as well as some specific solutions dedicated for inverters used in PV systems [20,21].

However, there are no papers which present an analysis and comparison of the three most popular types of renewable energy sources. This paper aims to present analyses which can help to draw more general conclusions, and which are supported by real measurements.

Although some papers [22] suggest that competitive forces rather than governmental interferences should shape the future of the energy system, we would like to join the other researchers [23,24] and draw the attention to some guidelines or steps which must be made at the national level when working on strategies devoted to the RES development. Otherwise, some problems concerning power quality and reliability will emerge. In our opinion, it is not enough to use both solar and wind RES to eliminate problems caused by the variability of these sources as suggested in [25,26]. This is not a universal strategy and can give satisfactory results only under some assumptions about local weather conditions. This was also a conclusion drawn in further works by the same authors cited above [27,28] which suggest the application of some means for long-term energy storage or keeping some balancing reserves based for example on thermal power plants [29].

In order to maximize the energy use and so the profits, the RES project should ensure that the local energy production and consumption are as highly correlated as possible. Such an approach requires advanced analysis and is sensitive to the future network changes or reconfigurations. The other solution consists in, as mentioned above, the application of large-scale energy storage to hold energy during overproduction periods and to release it during the highest demand periods [27,28]. Solutions based on energy storage in batteries, flywheels or superconducting magnets have become more and more popular but pumped storage hydroelectricity is the most common solution. Pumped storage is regarded as the most cost-effective form of mass power storage and the only problems are the
availability of natural water resources and high investment costs. Pumped water systems, like the hydroelectric power station near Olsztynek, have high dispatchability. It makes them very efficient at covering peaks in electrical energy demand. Therefore, when comparing the local variability in energy production and demand, one can plan a hydroelectric power station working regime in order to maximize utilization of all the three renewable energy sources. Moreover, a suitable control algorithm and cooperation between sources can help to increase the system stability. Currently the stability is not a problem but in the future the increasing number of RES, especially a high number of small PV systems installed by house owners, could make it a real issue. The situation reminds us of problems caused by a large number of low power nonlinear loads which a few years ago dominated the negative influence of large industrial loads and made existing power compensation systems inefficient and unable to cope with such problems.

The paper is based on measurements taken over a 4 year period in power stations representing three types of renewable energy sources (hydropower, wind and solar). They have similar power ratings and are located within a short distance of each other.

The paper consists of six sections including the introduction. Section 2 is devoted to a general characterization of these three exemplary renewable energy sources where the measurements used in the paper have been taken, while Section 3 describes in detail the energy production and efficiency of the three plants. The results of long-term analysis of the sources have been presented in Section 4, and the following section shows short-term analysis results. Section 6 addresses problems of power quality for each type of the renewable energy source. The paper ends with a discussion of the results and conclusions.

2. Characteristics of Renewable Energy Sources Used for the Analysis

All energy sources under consideration are located near the small city of Olsztynek (53.585968 N, 20.277693 E) in the Warmia-Masuria Province in northeastern Poland. The PV power station is connected to the network through an MV station (15 kV) which is supplied with the help of an overhead cable line (3 x XRUHAKXS 120/50 mm², 9.6 km length) from a HV/MV substation (S_SC = 1049 MVA in HV side, S_SC = 132 MVA in MV side) equipped with two transformers 110 kV/15 kV having power ratings of 16 MVA. The PV power station includes a MV/LV substation with 1 MVA transformer. The LV part delivers energy for the PV power station self-consumption as well supplying 6 cable connectors through a 2 x YAKY 3 x 240 + 120 mm² cable. The connectors have been used to connect 46 three-phase 20 kW inverters (SYMO 20.0-3-M) which transform energy collected from 4000 (43 x 88 + 3 x 72) monocrystalline PV panels having a rated power equal to 250 W. Thus, the total nominal power is equal to 1 MW. It can be observed that the 20 kW inverter connected to 88 PV 250 W panels each gives 10% overload for nominal values—the total inverter nominal power is 0.92 MW. The orientation of the panels is facing south with an angle of 30°. The PV panel parameters are given in Table 1. The simplified electrical diagram of the PV power station and its connection with the power system have been shown in Figure 3.

![Figure 3. Simplified diagram of the PV power station.](image-url)
Table 1. Basic parameters of PV module SFE.MF-6-250.

| Electricity Parameter          | Value         |
|-------------------------------|---------------|
| Nominal Voltage $U_{N}$       | 30.90 V       |
| Open Circuit Voltage $U_{OC}$ | 37.50 V       |
| Nominal Current $I_{N}$       | 8.10 A        |
| Short Circuit Current $I_{SC}$| 8.75 A        |
| Nominal Power $P_{N}$         | 250 W         |
| Module Efficiency $\eta$      | 15.4%         |
| Maximum System Voltage DC     | 1000 V        |
| Power tolerance               | 0 $\div$ +3% |
| Voltage Temperature Coefficient $\alpha$ | -0.05 %$/^\circ$C |
| Current Temperature Coefficient $\beta$ | -0.33 %$/^\circ$C |
| Power Temperature Coefficient $\gamma$ | -0.39 %$/^\circ$C |

The wind farm is connected to the power network through a MV station (15 kV) which is supplied with the help of an overhead cable line ($3 \times$ XRUHAKXS 120/50 mm$^2$, 6.5 km length) from a HV/MV substation ($S_{SC} = 1054$ MVA in HV side, $S_{SC} = 131$ MVA in MV side) equipped with two transformers 110 kV/15 kV having power ratings of 16 MVA. The wind farm includes a turbine VESTAS V100 with nominal power equal to 2 MW. Inside nacelle a three-phase and three-winding transformer having nominal power 2.1 MVA and a MV/LV switchboard are installed. The transformer main winding is supplied by an asynchronous slip ring-rotor generator—see Table 2 for its parameters.

Table 2. Basic parameters of asynchronous generator.

| Electrical Parameter          | Value         |
|-------------------------------|---------------|
| Nominal power $P_{N}$         | 2020 kW       |
| Stator nominal voltage $U_{1N}$| 690 V ($\Delta$) |
| Stator nominal current $I_{1N}$| 1530 A       |
| Nominal frequency $f$         | 50 Hz         |
| Nominal speed $n_{n}$         | 1680 rev/min  |
| Power factor $\cos \varphi_{n}$| 1.0          |
| Rotor nominal voltage $U_{2N}$| 480 V ($Y$)   |
| Rotor nominal current $I_{2N}$| 610 A         |
| Efficiency $\eta$             | 0.97          |

The third winding is used to supply wind farm self-consumption. The wind farm power is controlled by yaw drive and Vestas Converter Systems (VCS) which regulates voltage and frequency delivered to the rotor of the motor. The simplified electrical diagram of the wind power station and its connection with the power system have been shown in Figure 4.

![Figure 4. Simplified diagram of the wind power station.](image-url)
HV side, $S_{SC} = 153$ MVA in MV side) equipped with two transformers 110 kV/15 kV having power ratings of 25 MVA. A six-bay MV/LV substation is placed within the power station area. The power station is equipped with two hydrogenerator sets: a synchronous generator and an asynchronous generator (see Table 3). Both water turbines are propeller-type with adjustable blades (Kaplan turbines). The simplified electrical diagram of the hydroelectric power station and its connection with the power system have been shown in Figure 5.

![Simplified diagram of the hydroelectric power station](image)

**Figure 5.** Simplified diagram of the hydroelectric power station.

**Table 3.** Basic parameters of generators.

| Electrical Parameters        | Synchronous Generator | Asynchronous Generator |
|-----------------------------|-----------------------|------------------------|
| Power rating $S_N$          | 450 kVA               | 625 kVA                |
| Stator nominal voltage $U_{1N}$ | 5.25 kV             | 400 V                  |
| Stator nominal current $I_{1N}$ | 50 A                | 905 A                  |
| Nominal speed $n_n$         | 300 rev/min           | 1005 rev/min           |
| Rotor nominal voltage $U_{2N}$ | 110 V               | -                      |
| Rotor nominal current $I_{2N}$ | 66 A                | -                      |
| Power factor $\cos \varphi_n$ | -                    | 0.83                   |

### 3. Energy Production

This section is devoted to the comparison of energy production of renewable energy sources. The comparison is made on the base of exemplary long-term measurements taken in the power stations described in the previous section. The analysis spans a few years and allows us to draw general conclusions for RES located in similar locations, and which therefore are exposed to similar weather conditions. Seasonal changes and trends can be observed in energy production presented in Figures 6–8. The high season for the photovoltaic power station (from April to September) is at the same time a low season for the wind farm, so these sources complement each other. The production pattern for the hydroelectric power station is similar to that of the photovoltaic power station but its high season is asymmetrical, with higher production during the first quarter of a year.

Because the analyzed power stations are not identical in size, in order to make our energy production comparison more objective, in Figure 9 annual energy production in relation to nominal power has been presented. It gives information about the efficiency of each source—it is at a similar level for the wind farm and the hydroelectric power station, whereas three times lower in the case of the photovoltaic power station.
Figure 6. Monthly energy production for the photovoltaic power station in 2016–2019.

Figure 7. Monthly energy production for the wind farm in 2016–2019.

Figure 8. Monthly energy production for the hydroelectric power station in 2017–2019.
4. Long-Term RES Analysis

This section includes statistical analysis aimed at the evaluation of average loading of generation system for intervals reflecting different nominal power usage—from 0% to 100%. Moreover, the variability of the average loading has been also verified. Such an analysis allows us to evaluate the influence of a given RES on a power system.

Relative usage of both the photovoltaic power station and the wind farm varies significantly (Figures 10 and 11). In the case of the hydroelectric power station the variation is much lower (Figure 12) due to the manual control of output power and low variability of hydrological conditions (water level).

Even if a zero usage for the photovoltaic power station due to the night period is excluded, the wind farm demonstrates better power usage. For example, in the case of the wind farm the power usage greater than 50% of nominal power covers around 27% of the time in a 4 year perspective (Figure 11), while for the photovoltaic power station it is only 7.1% (Figure 10).
The changes of average power based on measurements taken every 15 min are lower for the photovoltaic power plant (Figure 13) than for the wind farm (Figure 14). The changes for the hydroelectric power plant are the lowest (Figure 15)—usually less than 2%. The relative short-term power changes are the highest for the wind farm, e.g., changes $\pm 15\%$ comprise 2.5% of all changes while changes $\pm 5\%$ comprise as much as 20% of all changes. The power changes for the photovoltaic power station are lower (most of the changes are less than $\pm 5\%$) but it is also a consequence of 15-min measurements and averaging caused by this data acquisition interval.
5. Short-Term RES Analysis

This section presents an analysis of the influence of daily energy generation changes on the power network. Each type of RES has different characteristics, sensibility and relationship with changes in weather conditions. The highest and sharpest power changes can be observed for photovoltaic power stations, especially when overclouding comes during the peak generation. On the other hand, wind farms show the highest change of power ranges depending strongly on gradient of current weather conditions.

This section does not include results for the hydroelectric power plant as it is a stable energy source and its variability comparing with the other two types of sources can be neglected in short time analysis. The energy production in the case of hydroelectric power stations depends only on the water stream set by the plant staff and except abnormal situations when the dam water level is very low, the power can be regarded as constant.

The generation of the photovoltaic power station depends strongly on weather conditions and contrary to averaged waveforms presented in Section 4 (see Figures 10 and 13), it can be easily observed in short-term waveforms (see Figures 16a and 17a). The variability of the generation in the case of the wind farm is also significant but not as high as for the photovoltaic power station–compare Figures 16a and 17a with Figures 18a and 19a, respectively.

The active power changes transfer directly to voltage changes in the point of common coupling. The correlation between active power and network voltage can be noticed especially in one-hour waveforms presented in Figure 17a,b in the case of the photovoltaic power station as well as to a lesser extent in Figure 19a,b in the case of the wind farm. This phenomenon may have had a direct influence
on power quality indices. It is worth noting that in Figure 17b a reaction of the voltage control system can be observed.

Analysis of voltage THD coefficient presented in Figures 16c, 17c, 18c and 19c leads to the conclusion that active power changes do not influence the content of higher harmonics in power system voltage. The voltage THD limit overrunning is not due to the wind farm, but it is rather caused by other loads or sources connected to the same network.

**Figure 16.** Exemplary one-day waveforms for the photovoltaic power station: (a) active power, (b) phase voltage—RMS value; (c) voltage THD.
Figure 17. Exemplary one-hour waveforms for the photovoltaic power station: (a) active power, (b) phase voltage—RMS value; (c) voltage THD.

Figure 18. Exemplary one-day waveforms for the wind farm: (a) active power, (b) phase voltage—RMS value; (c) voltage THD.
6. Power Quality RES analysis

Power quality problems are becoming more and more common due to the widespread usage of power electronic devices such as inverters, which are a crucial part of photovoltaic and wind power stations. In the case of hydroelectric power stations, the situation is different as they are based on electromechanical generators (see Section 2). This is the reason why this section is limited to RES with power electronic devices used for energy transformation.

Higher harmonics content in current waveforms depends strongly on the energy generation level and actual power in relation to nominal power. These factors have been analyzed in Sections 3 and 4. In accordance with the standards, which regulate the application of inverters in renewable power stations, for the nominal conditions the content of higher harmonics in waveforms cannot be higher than 5%. The exemplary measurement results presented in Figures 20 and 21 confirm that both the photovoltaic and the wind power station operation is up to standard.

It should be observed that an increased content of higher harmonics is possible if a power station works with power lower than the nominal one (see Figures 22 and 23), or if the number of such power stations operating in the same region is high and problems accumulate. It can result in a breach of the limit imposed on harmonic content by standards in the case of the network voltage, especially the fifth harmonic.

Furthermore, it may bring about increased losses in a transmission system, transformer overloads or disturbances in sensitive load operation.
Figure 20. Exemplary MV phase current waveforms for the photovoltaic power station for generated active power equal to 700 kW.

Figure 21. Exemplary MV phase current waveforms for the wind farm for generated active power equal to 1875 kW.

Figure 22. Exemplary MV phase current waveforms for the photovoltaic power station for generated active power equal to 25 kW.

Figure 23. Exemplary MV phase current waveforms for the wind farm for generated active power equal to 95 kW.
The current waveforms obtained for active powers close to nominal ones show low higher harmonic content for both the photovoltaic (less than 3.2%) and the wind power station (less than 1.2%)—see Figures 20 and 21. It is a result of standards that must be followed by companies producing inverters and moreover filtration of higher harmonics by MV/LV transformers. However, the problem of higher harmonics arises if the working point is far below nominal power (see Figures 22 and 23). The current THD coefficient for powers less than 10% of nominal power is above 12% for the photovoltaic power station and 7% for the wind farm. The results of the current and voltage THD coefficients for cases presented in Figures 20–23 have been shown in Table 4.

Table 4. THD coefficients for different power levels.

| Source | Power | THDi_L1 | THDi_L2 | THDi_L3 | THDu_L1 | THDu_L2 | THDu_L3 |
|--------|-------|---------|---------|---------|---------|---------|---------|
| PV     | 700 kW| 3.18%   | 2.93%   | 2.83%   | 0.82%   | 0.73%   | 0.73%   |
| Wind   | 1875 kW| 1.15% | 1.20% | 1.20% | 1.04% | 1.03% | 1.06% |
| PV     | 25 kW | 25.4% | 21.2% | 24.6% | 0.88% | 0.80% | 0.85% |
| Wind   | 95 kW | 19.6% | 17.5% | 18.5% | 0.94% | 1.09% | 1.05% |

7. Discussion

The power change rate can be evaluated on the base of the coefficient of variation defined as:

\[ c_V = \frac{\sigma}{\mu} \]  \hspace{1cm} (3)

where: \(\sigma\)–standard deviations, \(\mu\)–means value.

In order to simplify discussion of results some additional coefficients derived from Equation (1) may be proposed:

- coefficient for 15 min power measurements taken during all the period under consideration (4 or 3 years),
- coefficient for 15 min power measurements taken during all the period under consideration (4 or 3 years) and powers greater than 10% of the nominal power,
- coefficient for 1 s power measurements taken during a given day (in accordance with Section 5).

In the case of analysis of dynamics of power changes (Figures 13–15) the measure of variability can be calculated as a ratio of the change mean value and the nominal source power \(P_n\):

\[ c_\Delta = \frac{\mu_\Delta}{P_n} \]  \hspace{1cm} (4)

The calculated variability coefficients presented in Table 5 show that:

- the hydroelectric power plant is the least variable source regardless of which coefficient of variation is taken under consideration, which of course is unsurprising;
- the working cycle of the photovoltaic power station with no energy generation for more than half of the time makes the long-term variability expressed by more than two times greater than for the wind farm;
- the more realistic long-term comparison reflecting the different character of sources can be made on the base of the coefficient which also shows the greater variability of the photovoltaic station but only a quarter greater than it is for the wind farm;
- the variability for single days, i.e., the short-term variability, is lower than the long-term one for all analyzed sources;
- the variability of the averaged (15 min) power changes \(c_\Delta\) is relatively low (less than 5%) and it is the highest for the wind farm and the lowest for the hydroelectric power plant.
Table 5. Coefficients of variation for the analyzed sources.

| Source        | $c_{V(LT)}$ | $c_{V(LT_0)}$ | $c_{V(ST)}$ | $c_\Delta$ |
|---------------|-------------|---------------|-------------|-------------|
| PV            | 188%        | 93%           | 85%         | 2.1%        |
| Wind          | 89%         | 76%           | 59%         | 4.6%        |
| Hydroelectric | 53%         | 44%           | -           | 1.8%        |

8. Conclusions

A comparison of the long- and short-term behavior of the three most common renewable energy sources, i.e., a photovoltaic power station, a wind farm and a hydroelectric power station, has been presented in the paper. The sources under consideration have a similar size (nominal powers between 1 MW and 2 MW) and are located within a short distance of each other.

All three renewable energy sources have a repetitive monthly energy production in successive years. This allows us to estimate energy production at an early stage of new investments. The periodicity of production depends on geographical location and due to different high seasons in each case the sources can complement one another. The lowest production by wind and hydroelectric power stations observed in summer can be compensated by photovoltaic power stations with the highest production in this period. The efficiency of the wind farm and the hydroelectric power station, defined as energy production per 1 MW of installed power, is at the same level and more or less three times higher than for the photovoltaic power station. It should be considered when the payback period is estimated. Moreover, the wind farm operates more frequently at higher powers than the other sources (for 4% of time within the four-year perspective it works with the maximum power). The long-term analysis has confirmed the high repeatability of annual energy generation patterns for all sources.

Short-term analysis has confirmed that the photovoltaic and the wind power stations are highly varying sources depending on the weather conditions. The variation can influence the network voltage and thus the power quality in the supplying network (sags and swells). Nevertheless, any notable correlation between power changes of these sources and THD coefficient levels in the network has not been observed. It must be stressed that results depend highly on the quality and structure of the supplying network (line lengths, system impedance, etc.) as well as on the number of renewable energy sources in a given region.

Analysis of voltage and current waveforms for different source power levels lead to the conclusion that for powers close to the nominal one the current THD coefficients are very low (significantly below levels given in norms). The current THD coefficients increase considerably for lower source power levels, but it does not result in supplying voltage deformations. This problem can occur in the case of a large number of sources delivering low power, particularly small PV installations connected to the same substation.

The variability indices presented in the paper allow us to compare renewable energy sources. The photovoltaic system demonstrates the highest variability both in the short- and long-term perspective. However, the wind farm is a source with the highest variability of average 15-min power—almost two times higher than for the other sources.

Although the results presented in the paper do not show any power quality problems, and limits imposed by standards on THD or voltage variability are not exceeded, the variability of power generated by renewable energy sources remains a valid problem. Taking into account the high variability of solar and wind power stations, the increasing number of such sources connected to the power systems may cause considerable voltage fluctuations resulting in negative effects like flickering. This problem can be resolved with the help of energy storage, although it is an expensive solution which requires large-scale investment. A pumped storage hydroelectric power station is an example of such an energy reservoir, so the diversification of renewable energy sources in the same location is rewarding due to the system operation stabilization, as well as the balancing of the energy demand and its generation. Unfortunately, the hydroelectric power plant location depends strongly on geographical
conditions and thus before the invention of relatively low-cost and effective large-scale energy storage systems, the wind and solar power stations must be assisted by conventional power engineering.

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**Abbreviations**

| Term   | Definition                          |
|--------|-------------------------------------|
| THD    | Total harmonic distortion           |
| THDi   | Total harmonic distortion of current |
| THDu   | Total harmonic distortion of voltage |
| RES    | Renewable energy sources            |
| LV     | Low voltage                         |
| MV     | Medium voltage                      |
| HV     | High voltage                        |
| PV     | Photovoltaic                        |
| RMS    | Root Mean Square - effective value  |
| MW     | Electrical power unit used for active power - mega watt |
| MVA    | Electrical power unit used for apparent power - mega volt-ampere |
| $S_{sc}$ | Short circuit power                 |

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