Technical challenges in the application of renewable energy: A review

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Abstract

The aim of this review is to investigate the technical challenges involved in renewable energy distribution. One of the problems is that solar energy and wind power only generate energy when it is windy or the sun is shining. This work presents a possible solution to this problem. Solar energy and wind power are increasing power generation forms globally. Yet, some technical challenges exist in integrating solar energy and wind power in the electricity network. For example, wind speed changes the rotating speed of windmill plates causing changes to the voltage, frequency, and power.

However, an integrated renewable energy supply and energy storage system connects solar and wind to a battery system, ensuring electricity production without adding non-renewable sources. Applications can be near consumption places like houses, remote towns, factories, and research stations. In this study, renewable energy and energy storage system integrates vehicle to grid operations to reduce fluctuating power.

As a result, grid connections to large-scale and small-scale solutions are presented. Presented grid connections stabilize fluctuating power system. Increasing penetration of renewable energy needs balancing power. The combination of renewable power, batteries, and electric vehicles are a solution for balancing fluctuating power frequency and voltage.

Keywords: Electric vehicle; energy storage; power flow study; remote region; vehicle to grid operations

1. Introduction

Energy production and consumption are the largest sources of pollution and because of the concern about environmental risks, a need to reduce both energy production and consumption emerges [1]. Environmental risks are higher in populated and industrialized areas. Different pollution effects exist as a consequence of the technology used. These environmental issues are the driving force to increase the share of renewable energy supply in power production [2]. However, solar energy and wind power cause a negative effect on the power quality and reliability of the electricity network [3, 4]. Wind power reduces voltage and network frequency quality in the electricity network. Additionally, wind power increases the need to stabilize the network load to balance consumption and production during wind generation [5]. The control system is matching supply and demand [6]. An increased amount of wind power means an increased amount of control devices needed to stabilize the grid. Wind speed changes, causing alternating power to feed to the power grid. Therefore, the difference in voltage, frequency, and phase needs a larger short circuit power to connect wind power generation to the power grid.

Wind power increases the need for operating reserves in the electricity network [7]. The surplus production may have to be reduced to keep a real-time balance between production and consumption [8]. To receive constant power, renewable energy needs to integrate with the energy storage system. The energy storage system may increase the needed current and current dependent energy losses [9]. Planning energy storage systems include the type of storage, size of storage and location of storage [10]. A wide

range of renewable energy-based research is published; however, technical problems of electricity supply systems are not well discussed.

The resent study consist of several review articles, which study technical challenges in the application of renewable energy. A review article of status, future prospects, and their enabling technology describes grid integration infrastructure and technical barriers for renewable energy technology deployment. Renewable energy integration technical challenges are power system planning and risk management, generation prediction, energy storage, reliability and security [11]. A review article of challenges with renewable energy supply and energy storage systems in distribution networks presents energy storage algorithms in the distribution network. These algorithms are integrated solar energy or electric vehicles, valley filling algorithm, battery energy storage system, rapid charging navigation algorithm and load flow rolling optimization [12]. A review article of renewable energy integration to smart grids describes a Low Voltage Ride Through (LVRT), which has the capability of electric generators to stay connected in short period of time in low power grid voltage. LVRT prevents a short circuit at power grid from causing a widespread loss of generation at the distribution level. An uninterruptible power supply or capacitor bank handles similar requirements for critical loads, such as computers and industrial applications to supply uninterruptible power during low power grid voltage. A review paper describes LVRT capability enhancement methods and inter-area oscillation damping in power systems. The inter-area oscillation may occur when a long transmission line connects generation and load. The low-frequency oscillation introduces instability to the power grid when abnormal situation occurs and limit power transfer capability in long power transmission lines. Power lines have damping control to compensate for stability. Renewable sources with energy storage can enhance stability in the power grid, such as inter-area oscillation damping. [13].

The integration of renewable energy systems to power grid conduct for emerging power quality challenges. Therefore, power quality is a critical aspect of renewable energy supply systems. The major power quality challenges are voltage and power frequency fluctuations and harmonic frequencies [14]. Renewable energy sources are intermittent power supply due to the variating weather conditions. Renewable energy resources variability increase power grid voltage and power frequency fluctuations. The energy storage enhances power quality for the integration of renewable energy systems. The value stream mapping method is a promising solution for damping voltage and power frequency fluctuations. Voltage and frequency control covers the value stream mapping combined with other methods, such as reactive power compensation. The reactive power compensation mitigates the reactive power in power supply and transmission. Renewable energy resources utilize power electronics, which generate harmonic frequencies. The influence of harmonic frequencies is significant at high penetration renewable energy supply. The virtual impedance method compensates harmonic frequencies. The converter control schemes include the virtual impedance method, which improves the system stability by damping the natural oscillations. Harmonic spectrum measurements investigate harmonic characteristics for wind and solar power systems. Harmonic frequencies increase heating in power equipment. The control schemes for inverters reduce harmonic frequencies and power grid disturbances for enhancement of renewable energy sources LVRT capability [14].

A review article of renewable energy supply in China discusses integration management, challenges, and solutions. Integrated renewable energy and energy storage systems for large applications have challenges on operational, organizational, and incentive policy management [15, 16]. A review article of the integration of wind power presents the major challenges with the integration of renewable energy into interconnected power grids. Technical challenges are operating costs of the power system, power quality, imbalances in power system, power system dynamics and effects on power transmission lines [17].

The key issues of technical challenges in implementation on microgrids are voltage and frequency fluctuations, islanding detection and protection systems [18]. Identifying the technical challenges, such as detecting islanding situations, harmonic distortion requirements and electromagnetic interference requirements for grid interconnection lead solutions for renewable energy applications [19]. A review article of technical challenges in distribution network discusses transient stability in the smart grid.

Intermittent renewable energy resources mitigate the power grid transient stability. Therefore, integration of renewable energy resources is one of the major challenges in the power grid [20].

Literature references introduce technical challenges in the application of renewable energy supply systems. Not so many literature references coveted renewable energy supply and energy storage systems integrated to Vehicle to Grid (V2G) operations. The research problem is that integration of renewable energy has reliability and power quality issues. The objectives of this study are to review technical challenges in the application of renewable energy systems and integration of V2G operations to the power systems. Purpose of the study is to identify key challenges to establish a foundation for the development of technical solutions. This research used available review articles and recent research on technical challenges in the application of renewable energy systems. The contribution of this review is connecting all these considered technical challenges to the integration of V2G operations. The novelty of this work in relation to the similar work is the usage of V2G operations in renewable energy distributed generation system.

The remaining of this paper is structured as follows. Section 2 discusses variable generation technologies, technological issues, and compensation. In section 3, the power flow investigation in power systems engineering is connected to renewable energy systems. The voltage and frequency fluctuations are described as major power quality issues. The voltage and frequency control systems are reviewed in sections 4 and 5. Section 6 discusses renewable energy in large applications and section 7 discusses renewable energy in remote regions. Finally, discussion and conclusion summarize the main results and conclusions of the review.

2. Compensating Variable Generation

The main objective of compensating variable generation is to mitigate the dependence of microgrid on the power grid during uncertainties in power quality generated by the renewable energy supply [21]. Variable generation technologies, such as solar energy and wind power have different characteristics in comparison with traditional power generation methods. Wind power increases variability in network power, voltage and frequency and wind resource uncertainty in the existing electricity network system [22]. Consequences are fluctuations in power, which needs to be compensated by regulating the power system.

These variabilities and uncertainties can be reduced by locating power storage systems near the wind turbine. Power storage can improve the reliability and quality of the electricity network by supporting energy to the network when power generation levels are too low. Superconducting magnetic energy storage can load energy in the electromagnetic field, which is generated by direct current flowing through the magnetic coil. However, superconducting magnetic energy storage is only suitable for short period storage. Long period storage could be organized by the battery storage system.

Among other energy storage systems for the power grid, electric vehicles with Vehicle to Grid (V2G) features are promising storage methods. The V2G can significantly reduce excess renewable energy in grid systems [23]. The V2G can provide frequency regulation and enhance power quality in the power grid [24]. Hybrid storage combines long period storage and short period storage. Hybrid storage generates energy for both short period and long period usage. Performance of the renewable energy supply system and the battery storage system can be handled together or separately. Evaluation of this system performance has been done by both mathematical and simulation models [25]. The model showed that placement of storage near the generation place avoids long transmission. However, other location options for energy storage can be considered. Location of energy storage system is not restricted to a specific place and energy storage system can be located in any location in the power system [25]. V2G operations provide distributed battery storage for the power grid and location variates constantly.

3. Power Flow Study on the Transmission Network

Power flow in power systems engineering investigates voltage magnitudes and phase angles for the

busbar system and investigates each busbar individually. Power flow examines the best operation for the power system and it is used to plan new expansions for power systems. A power flow study compares these busbar voltage magnitudes and phase angles to another busbar system where a set of busbars was known [26]. The flow of electric power was solved with numerical analysis using a linear model for transmission lines, transformers, and reactive power. Generation and load in power systems were analyzed with a nonlinear model because the power flow through the impedance Z is a function of the square of the voltage of the system. Network power flow equations in nonlinear cases are formulated from Kirchhoff's current law [27]. Nonlinearity can come from active and reactive power from distribution connections. Another source of nonlinearity is due to power stations use constant active power with voltage regulation [28]. However, differences of voltage phase angles between power generators on the system are not known in this model. The power flow study obtains information of the voltage phase angle for each busbar in a renewable energy supply system. Several power flow methods exist to solve nonlinear equations. The algorithm of the power flow problem can solve and investigate the performance of the integrated power system.

The power equation defines complex power S_k into a busbar using admittance matrix elements Y_{kj} [26]:

$$S_k = V_k \sum_{j=1}^{N} Y_{kj}^* V_j^* \tag{1}$$

Opening Equation (1) to form where we have S_2 and S_3 as a function of voltages and admittances:

$$S_2 = V_2 \cdot (Y_{21} \cdot V_1 + Y_{22} \cdot V_2 + Y_{23} \cdot V_3)^* \tag{2}$$

$$S_3 = V_3 \cdot (Y_{31} \cdot V_1 + Y_{32} \cdot V_2 + Y_{33} \cdot V_3)^* \tag{3}$$

Equations were rearranged so that the wanted unknown voltage could be calculated.

$$V_2^{k+1} = \frac{1}{Y_{22}} \left[\left(\frac{S_2}{V_2^k} \right)^* - Y_{21}V_1 - Y_{23}V_3^k \right] \tag{4}$$

$$V_3^{k+1} = \frac{1}{Y_{33}} \left[\left(\frac{S_3}{V_3^k} \right)^* - Y_{31}V_1 - Y_{32}V_2^k \right] \tag{5}$$

$$V_i^{k+1} = \frac{1}{Y_{ii}} \left[\left(\frac{S_i}{V_i^k} \right)^* - \sum_{j=1}^{n} \left(Y_{ij}V_j^k \right) \right], i \neq j \tag{6}$$

Fig. 1 shows the integrated system, where generated power to the utility distribution network is targeted to the constant value. Fig. 1 shows the single-phase equivalent circuit of solar energy and wind power supply using electric vehicles and batteries as energy storage. This is a simplified model of a transmission line for understanding the concept. Voltage and power can be calculated in every position in the integrated power system. For example, the impedance matrix has values $Z_{21} = 0.05 + j0.1$, $Z_{31} = 0.02 + j0.1$, $Z_{32} = j0.05$, $Z_{11} = -j100$ and $Z_{33} = -j40$.

In this example, generation from wind and solar is 200 kW and load 100 kW, 100 kVar. Load from energy storage is 300 kW, 50 kVar.

As a result, the Gauss-Seidel method iteration gives voltage magnitudes and voltage phase angles $V_1 = 415V(\varphi = 0°)$, $V_2 = 396.4V(\varphi = -6.979°)$ and $V_3 = 376.3V(\varphi = -0.685°)$. Power flow simulation was configured in an islanded situation [29]. The highest number of voltage variations and short-circuit current values were detected in the maximum load conditions.

Renewable energy supply system integrates solar energy, wind power, energy storage systems, V2G operations, inverters, and power control systems constructing a completely renewable energy supply system [30]. Renewable energy supply system increases voltage and power frequency fluctuations to the power grid. Small intermittent energy systems do not influence voltage and power frequency fluctuations to the power grid because the power grid is able to absorb small-scale voltage and power frequency fluctuations [30]. However, large-scale intermittent renewable energy sources increase technical challenges to the power grid. Remote area power grids are small-scale or medium size power systems. In

remote area power systems, operational challenges may become acute. Transient stability is an ability to keep synchronism in the power system. Maintaining synchronism is an operational challenge in small power systems. Transient stability analysis analyzes systems ability to remain synchronism following a disturbance for maintaining synchronism in the power system. Power grid planning analyses voltage and frequency fluctuations in normal and abnormal operational conditions. A power system analysis takes into account power disconnections, start-ups as well as short circuits in a power grid [31]. Fig. 1 shows the renewable energy distribution network with energy storage and V2G operations. Generating busbars connect intermitted energy, such as solar energy and wind power to the distribution network. The system controller integrates and optimizes V2G operations, battery storage, solar energy, and wind power to the renewable energy supply system. The mathematical model can solve the power flow problem and provide efficiency to the integrated power system. Energy storage and non-intermittent renewable energy resources, such as biomass and hydropower energy can compensate for intermittent solar energy and wind power. Biomass and hydropower stations provide energy when solar energy and wind power supply is low or not available. Renewable energy sources may not supply enough power at peak demand time. Peaking power plants run when peak demand for electricity emerges.
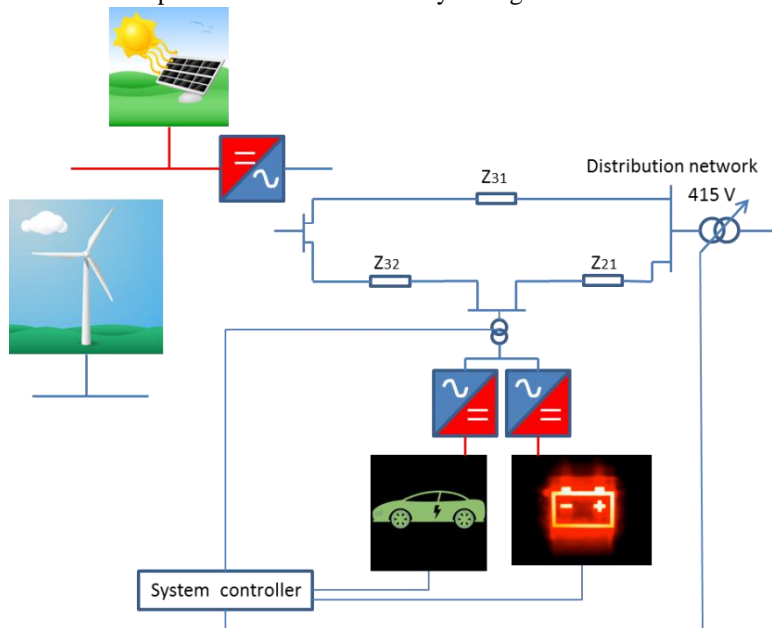

Fig. 1. Integrated solar energy, wind power, battery storage, and vehicle to grid operations connected to the small-scale renewable energy distribution network

4. Voltage Control System

Voltage level formally distinguishes electric transmission and distribution systems. A load tap changer in transformers controls constant voltage at the substation and with a voltage control relay as seen in Fig. 2. Automatic voltage control includes resistive, capacitive, and inductive loads to ensure full operational voltage control. Since the voltage decreases toward the end of the feeder, automatic voltage control ensures that the voltage is inside the allowed area [32].

A static synchronous compensator (STATCOM) provides variable reactive power in response to voltage variations. STATCOM compensates the voltage fluctuation and mitigates the variable reactive power demand of the renewable energy distribution network. Reduced reactive power demand enhances the power factor regulation and mitigates the harmonic distortion. Battery storage and V2G operations enhance the voltage regulation, mitigates active power demand from the power grid, and enhances transformer utilization level of the renewable energy distribution network. Therefore, integrated

STATCOM, battery storage, and V2G operations enhances voltage regulation, power distribution, transformer utilization level and mitigates the total harmonic distortion of the distribution network [33]. The integration of optimized STATCOM, battery storage, and V2G operations support the stability of the power grid and enhances the power quality of the distribution network.
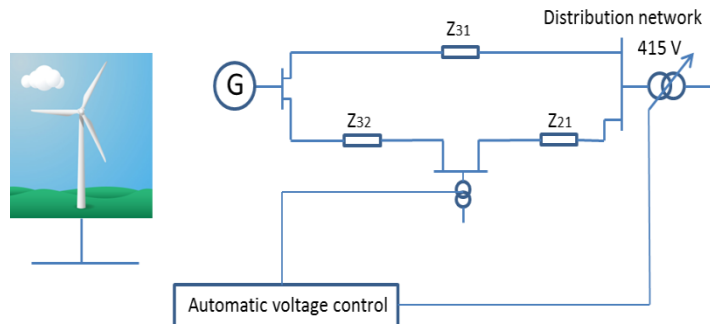

Fig. 2. Automatic voltage control includes resistive, capacitive and inductive loads and regulates voltage using voltage transformers.

5. Frequency Control System

The system frequency comes from the generator's rotational speed. The wind turbine rotates the generator according to wind speed. Overgeneration increases system frequency. Wind generators increase unbalance by reducing the inertia of the power system. Load ramps, swings, noise and jumps increase frequency unbalances to the power grid [34]. Fig. 3 shows frequency control where the generated current is first rectified to direct current and then inverted back to alternating current with line commuted regulated frequency. The smoothing inductor L between rectifier and inverter reduces the harmonic current level and the output voltage ripple.

Frequency control study presents frequency response capabilities of the wind power system. The wind power system can contribute to technical challenges by enhancing frequency regulation. However, frequency regulation demands a short period of time weather forecasts to integrate intermitted wind power system to the distribution network. [35].
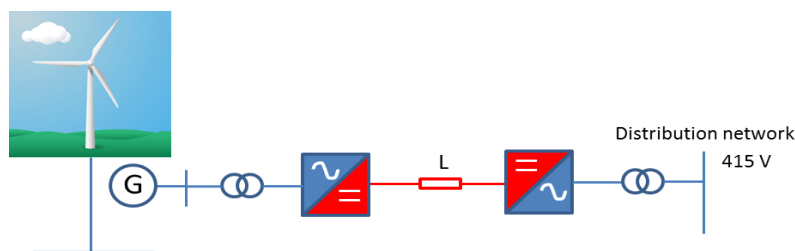

Fig. 3. Frequency control system modulates frequency by using a rectifier, smoothing inductor L and inverter units.

Finally, frequency control, power control, and voltage control need to link together as seen in Fig. 4. These three control units keep power balance, voltage and frequency deviations in reasonable ranges [36]. The utility network receives power from the combination of these three control systems.
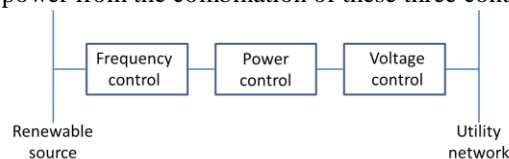

Fig. 4. Three control units supply power to the utility network.

6. Integrated Renewable Energy and Energy Storage Systems for Large Applications

Renewable energy and energy storage systems in distributed generation include technical challenges, such as reliability and power quality challenges. Reliability challenges depend on weather conditions. The electricity generation that intermittent renewable energy sources, such as solar energy and wind power can generate to the power grid depends on weather conditions. Variating weather conditions provide inconstant sun radiation and wind velocity; therefore, solar energy and wind power systems provide intermittent energy to the distribution network. Hence, a high penetration level of renewable energy generation can increase reliability challenges to the power grid.

Power quality challenges are voltage and frequency fluctuations and harmonic frequencies. Electrical devices are sensitive to voltage fluctuations [37]. Level of voltage and frequency fluctuations and harmonic frequencies indicate the power quality of a distribution network. Over-voltage and under-voltage are challenges particularly in high penetration level of renewable energy generation. Voltage fluctuation is an issue when the power system integrates intermittent power sources. Voltage fluctuates during starting and stopping wind turbines. Voltage fluctuation is particularly noticeable when a large-scale wind power system is integrated into a weak power grid [37]. Harmonic frequencies heat electrical equipment. Power electronics is one source for harmonic frequencies. Other major technical challenges are wind turbine noise levels. Power quality challenges increase as renewable energy distributed generation increases.

A location of renewable energy distributed generation impacts on the power system voltage. As renewable energy distributed generation increases, the power flow problem becomes more problematic. Voltage fluctuation is higher in low voltage network than high voltage network. Many large wind power generators feed electricity into the medium voltage electricity network and wind power generators can feed electricity even to the low voltage electricity network [37]. Low voltage inverters connect domestic solar arrays to a low voltage network. A need for the high voltage network emerges when a large solar energy plant feeds power to the distribution network. In such cases, transformers have an automatic tap changer to control fluctuating voltage [37].

Renewable energy distributed generation is connected to the power grid at the connection point. Choosing the connection point can cause challenges in power quality. Connecting renewable energy distributed generation at the load side of electrical load or transformer side increases power fluctuation. Consequently, power fluctuation has an impact on the power system voltage. Power fluctuation at low voltage side increases voltage fluctuation. Depending on renewable energy penetration level, renewable energy distributed generation might increase voltage, particularly during low load situations. To avoid voltage increase, a controller at the low voltage network controls the voltage [37].

Electricity consumption varies from low consumption time to high demand time. Usually, the lowest consumption is at night when people are sleeping. During low consumption time, power stations need to idle generators to ensure power when needed. At the low consumption time, energy storage can provide economic power to replace idling generators. In contrast, at peak demand time, high generation capacity is needed to ensure power meets the increased demand. In addition, during the peak demand time, expensive forms of power production are connected to the grid. Furthermore, during peak demand time, energy storage can replace the expensive short-term power stations, such as diesel generators.

Energy can be stored, for example, to pump water, compress air, charge batteries and electric vehicles, rotate flywheels and magnetize superconductors [38]. From these alternatives, pumped water is commonly used as energy storage. Pumped storage capacity is 740 MW in Australia [39]. The major part (97%) of utility-scale electricity storage in the United States comes from pumped water [40]. However, electric vehicles may provide virtual battery storage for the distribution network. A combination of renewable energy generation, battery storage, and V2G operations can provide a reliable and efficient system to utilize the power grid. Efficiency is an important part of the sustainable development of electricity generation [41]. Most of the renewable energy resources, such as solar energy and wind power are intermittent energy resources. Intermittent energy resources should be used in combination, alongside a continuous type of renewable energy resources, such as hydropower and biomass power generation. The

combination of renewable energy resources has three possibilities for energy storage: battery storage, hydro energy storage and hydrogen storage (Fig. 5).

To lower cost and improve reliability, energy storage should also be connected to an interconnected grid. Baseload power generators have low marginal cost while peaking power generators have a high marginal cost. For economic reasons, power generators have different operation times to peak demand time and baseload time. To ensure reliability renewable energy supply system, hydropower, biomass energy, and energy storage should be available for power supply. The nature of hydropower, biomass energy, and energy storage is short-term power with a high marginal cost that is why they are used for peaking power plants. Energy surplus is stored in the storage system. Electric vehicle batteries, batteries storages, and hydro dams can be used for storage purposes; thus, an increase in the number of electric vehicles and pumping stations can increase energy storage capacity. The existing electric vehicles can be upgraded to have a vehicle to grid features and hydro dams can be equipped with pumping facilities. Additionally, the upgrade systems are an economical way of building energy storage. Another way is to use solar energy with hydrogen storage.
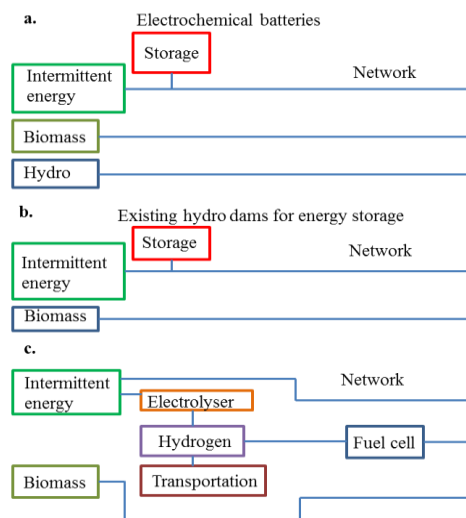

Fig. 5. Renewable energy large-scale systems include intermittent energy, biomass, and hydropower as well as energy storage facility. a. battery storage, b. hydro energy storage and c. hydrogen storage.

A combined solar energy and hydrogen storage systems can supply energy to the power grid. For example, the South Australian government has released a plan to build the largest co-located solar energy, wind power, and hydrogen production facility in the world. The initial plan is to combine the 150 MW of solar energy and 150 MW wind power with the 50 MW hydrogen electrolyzer and up to 400 MW of battery storage [42]. In the solar hydrogen system, the solar-powered electrolyzer converts water to hydrogen and oxygen and fuel cells can produce electricity from hydrogen and oxygen. Electricity can be stored in hydrogen. Hydrogen will enable thermal, mechanical, and electrical energies. Fuel cells can convert hydrogen into electricity. Fuel cells do not have the same limitations as heat engines have. Therefore, hydrogen fuel cells' efficiency would be higher than the efficiencies of heat engines and conventional power stations.

7. Renewable Energy in Remote Regions

Typical power production problem in remote regions is the shortage of electric power supply [43]. In remote regions, the power supply is often diesel generator based, which is designed for the peak demand generation. The size of the diesel generators needs to be at least four times larger than average demand [25]. The diesel generators run with uneconomical low power mode. Oversizing diesel generators mean relatively high investment, maintenance, and fuel costs. Diesel generators have an automatic start and

stop procedures for controlling running times and reducing fuel consumption. However, battery energy storage can reduce the running time for a diesel generator. Fig. 6 introduces an integrated renewable energy system, which integrates power sources, battery storage, V2G operations, and rectifiers, smoothing inductor L, inverters, and diesel generator. Battery storage and V2G operations utilize optimized battery charging-discharging cycles. Optimized battery life means that batteries supply power in the low demand time and diesel generators supply power on the peak demand time. Battery wear can be reduced by keeping the State of Charge (SoC) near the optimum point, usually 50% SoC [44]. Diesel generator systems are connected to the power grid without renewable energy sources. Energy storage enables intermittent energy, such as solar energy and wind power to be included in the power system, as seen in Fig. 6.
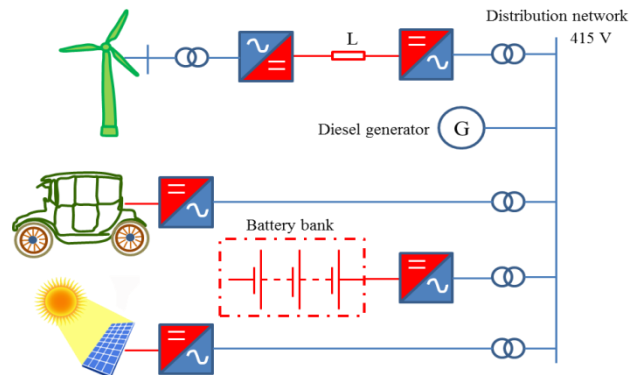

Fig. 6. The vehicle to grid system balancing power grid in remote regions. Electric components are a rectifier, smoothing inductor L and inverter.

8. Interpretation and Discussion

Renewable energy and energy storage systems in distributed generation include technical challenges, such as reliability and power quality challenges. Reliability challenges depend on weather conditions. Weather conditions determine sun radiation and wind velocity, which solar energy and wind power transform into electricity. The major quality challenges are voltage and power frequency fluctuations and harmonic frequencies.

The main solution for quality challenges is a static synchronous compensator. Integration of an optimized static synchronous compensator enhances the voltage regulation and mitigates the reactive power demand of the power grid. A static synchronous compensator enhances the power factor and mitigates the total harmonic distortion. Integrated energy storage mitigates active power demand, enhances the voltage regulation and transformer utilization factor of the renewable energy distribution network. A combination of a static synchronous compensator and energy storage facility combines these benefits together. A static synchronous compensator and energy storage enhance voltage regulation, power distribution and transformer utilization factor and mitigate total harmonic distortion. Therefore, integration of a static synchronous compensator and energy storage enhances the power quality of the renewable energy distribution network. The outcome of this study is a guideline to the power utilities for integrating vehicle to grid operations into the renewable energy distribution network.

9. Conclusion

Several different types of power generation need to be included in any power system. These include conventional sources and more environmentally friendly renewable sources, large-scale and small-scale sources. Smart grid solutions give more possibilities to define this combination. Small-scale systems may become more common in the future, giving distributed generation instead of centralized generation. The power flow study optimizes power systems and can be used to calculate the expansion of new network

parts. While intermittent generation causes voltage and power frequency fluctuations and reduces the reliability of the grid, integrated renewable energy supply, and energy storage may improve quality, voltage, and frequency. Vehicle to grid systems may be an important part of the energy storage in the future. Additionally, an integrated renewable energy supply and energy storage have large-scale and small-scale applications in populated areas as well as remote regions. This will provide quality and reliability to the grid and ensure an environmentally safer future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Both authors, Ph.D. student Timo Lehtola and A. Prof. Ahmad Zahedi, conducted the research, wrote the paper, and had approved the final version.

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