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Impact of The Penetration of Renewable Energy on Distributed Generation Systems

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ABSTRACT:
As the proportion of total generation by renewable sources compared to non-renewable sources increases, the relative inertial stability provided by large rotating generators in electricity grids is found to shrink and is not being replaced by sources such as photovoltaic and wind power, which are already known for their inherent variability. This leads to electricity generation systems being less stable, less flexible, and less adequate in applications with a high diversity factor, and literature shows that the penetration of renewable energy sources in distribution-generation/microgrid system frequently presents several technical and economic challenges in their usual applications. This work examines how increased renewable energy penetration impacts the distribution-generation system and suggests approaches and measures for tackling the challenges that are associated with it.

KEYWORDS: Renewable Energy, Distributed Generation Systems, Electricity Generation

1. INTRODUCTION

Renewable energy is the energy that is obtained from sources which are practically inexhaustible, mainly the self-sustaining regular, uninterrupted, or predictable processes that occur in nature. This category of energy includes the energy from the sun, which, strictly speaking, is our solar system's gigantic naturally-occurring nuclear reactor, although on earth it is experienced and therefore harnessed as a self-sustainable source of heat and light all over the globe [1–[3]. Renewable energy also includes energy from below the earth's crust, flowing from the molten furnace that lies in the center of the terrestrial geoid, and which is more than can be exhausted in the foreseeable future [4]. Gravity also interacts with the matter on earth to do mechanical work. These sources of energy are frequently transformed into intermediate forms such as hydropower, tidal, wind, and biomass by forces of nature[3].

A range of factors, majorly including sustainability and environmental concerns, relatively lower running costs, advances in electronic technology, and the need for supplementation of existing generation resources have encouraged a modern trend of renewable methods being increasingly preferred over non-renewable methods of electrical energy generation globally[5-7]. Despite the significant financial investments that are usually associated with the gradual transition to the age of renewable energy [8], it continues to gain traction in the twenty-first century due to climate change concerns and the attractiveness of independence from fossil fuels [9-11]. Energy that was produced from renewable sources made up about one-fifth of the United States' electricity generation and about one-tenth of its consumption in the year 2020 [12]. Also, renewable energy accounted for almost a fifth of the energy consumed in the European Union territories in 2019 [13]. Figs. 1 and 2 show the growth of renewable energy in the world in recent decades up to the year 2020[14].

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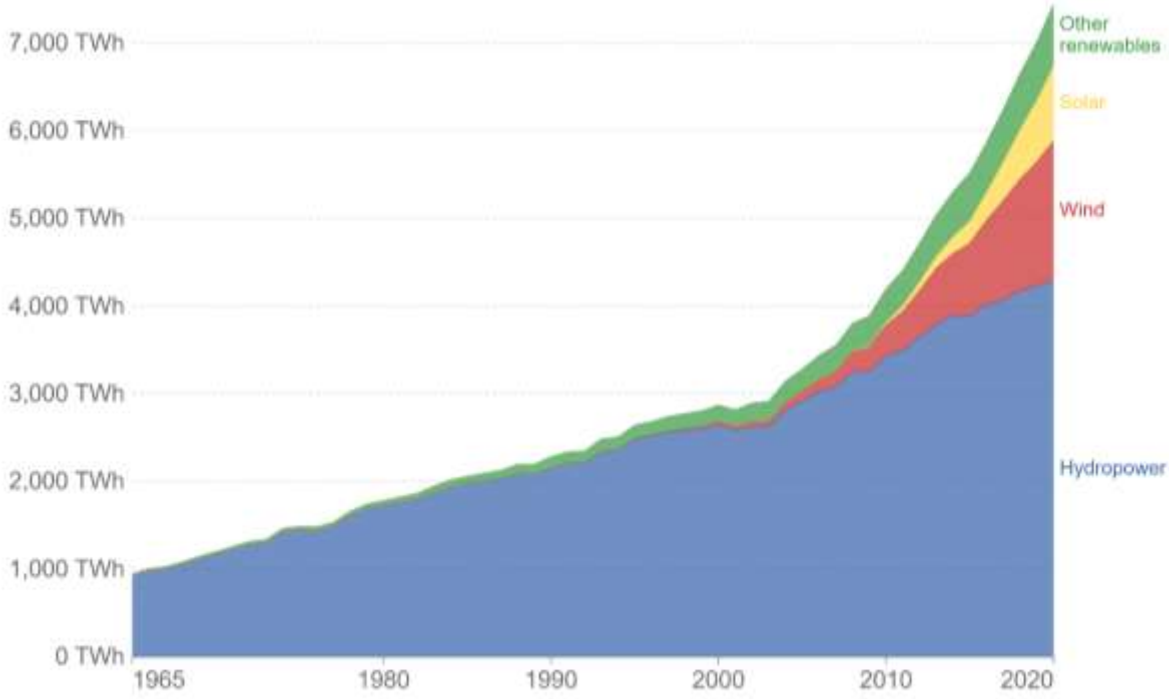

Fig. 1. Total World Renewable Energy Generation From 1965 to 2020 [14].

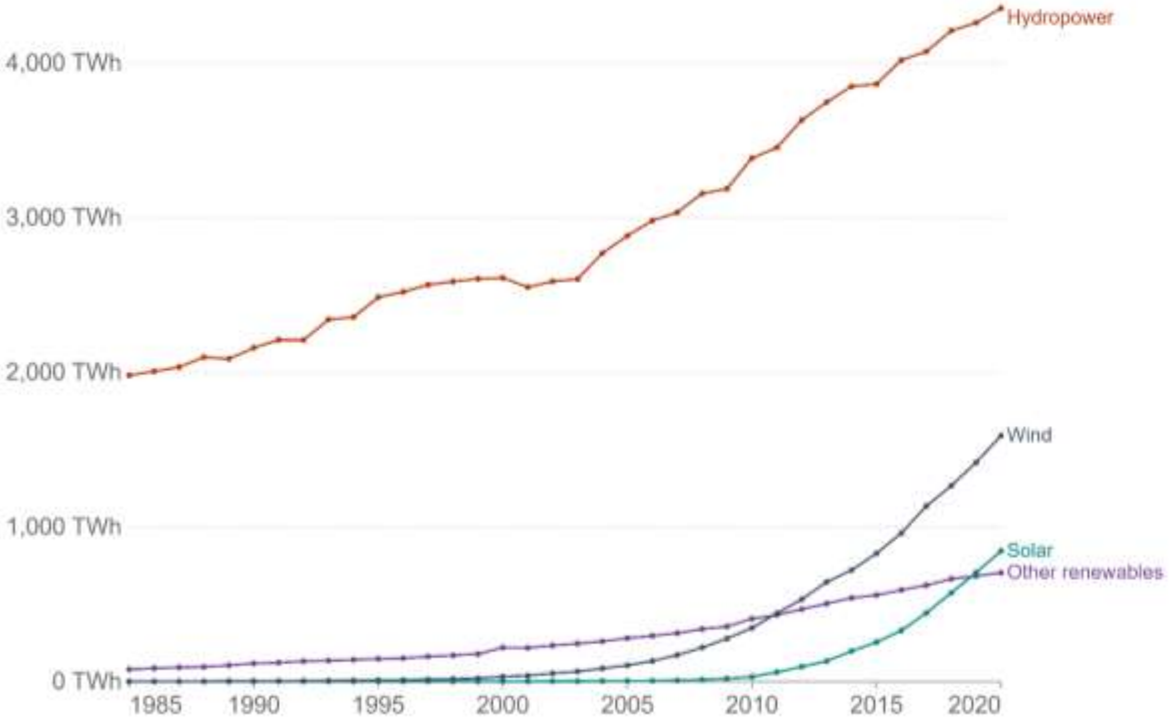

Fig. 2. World Renewable Energy Generation by Source From 1985 to 2020 [14].

As can be seen from Figs. 1 and 2, wind and solar power technology, in addition to hydropower, are the fastest growing energy generation technologies in the twenty-first century. Of the three, hydropower has been previously existent as a major renewable technology for electricity generation. Traditional methods of generating electrical energy for community/national usage have mainly relied on the production of electricity through electromagnetic induction in large machines that are mostly driven by steam power or moving water (hydropower)[15]. Historically, these energy generation facilities were mostly considered appropriate for establishment in considerable distances away from populated areas, where the bulk of the load is usually found [16], [17]. This was the case sometimes because of the hazardous environmental impact of these installations (as in the case of fossil-fueled and nuclear-fueled power plants) or because of the special conditions needed for the siting of such installations (as in the case of hydro-electric power plants) [18]. The power systems were built to be as centralized as possible, so that as few generating plants as possible were needed, which was a contributing factor to the sizes and scales of the machines chosen. This approach to grid implementation also required long, expensive transmission lines with significant losses along them[19].

However, the introduction of renewable energy generation systems using technologies such as photovoltaic (PV) arrays and wind turbines has mitigated the environmental impact factor of generation equipment mainly due to the fact that they do not emit by-products of combustion. This resulted in the option of bringing generation resources much closer to load centres and has been accompanied by the introduction of an element of stochasticity in the dynamics of power generation and transmission systems that was not present in the era of electrical grids having a few large synchronous generators, designed, matched, and with controlled mechanical energy inputs, as their power source[5], [20].

Denmark is one of the world leaders in renewable energy adoption, with wind and solar energy composing over half of the nation’s electricity consumption in 2020[21]. Fig. 3 shows the extent of decentralization of energy generation in Denmark between 1990 and 2014, illustrating how the country went from having a few big power plants to numerous smaller power plants.

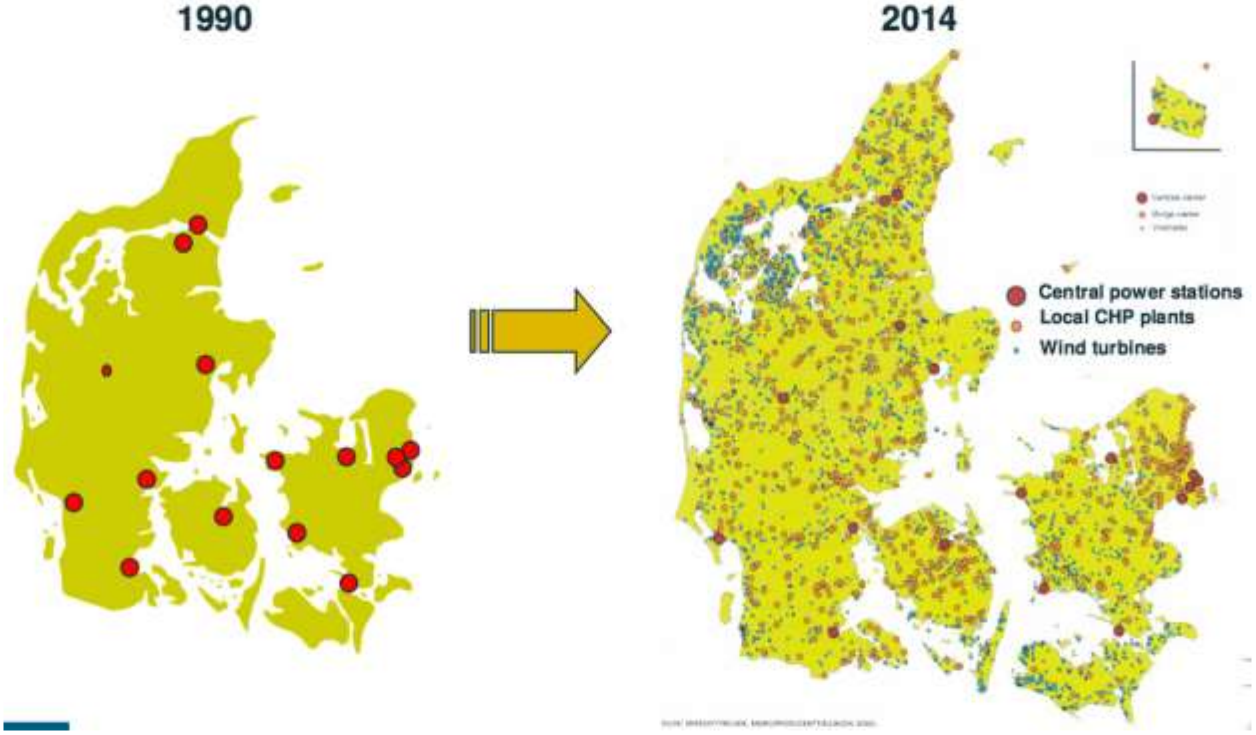

Fig. 3. Extent of Decentralisation of Denmark's Electricity Generation[22].

In contrast to fossil-fuel generator-dominated electricity grids, grids with a significant proportion of generation being contributed by resources such as wind and solar power are inherently variable in their supply of input energy, being very sensitive to uncontrollable climatic factors such as variance in wind patterns and insolation. The interactions of the solid-state electronics components in such large-scale generation and transmission systems are also known to introduce complications into their operation due to properties such as nonlinearity and the introduction of harmonic distortion[23][24].

2. LITERATURE REVIEW

Distributed Generation (DG) is a paradigm that in addition to decentralizing electricity generation, aims to minimize the travel path of electricity from the generating equipment to the end users. With the trend of electricity deregulation globally, there has been increased penetration of renewable resources which has made DG a more attractive alternative to the traditional, centralized generation-transmission method. A recurring theme in DG technology is a kind of electricity sub-grid, known as a microgrid[25]. These are networks that contain their own generation sources, configured so that they are not only able to draw and supply power from and to the larger grid but are also able to supply their connected loads while functioning in full island mode. The microgrid is designed to have both the autonomy of off-grid systems and the stability and integration and parallelization-based reliability of the larger grid[26]. Fig. 4 shows the difference between distributed generation and the traditional, centralized architecture of power generation.

Microgrid systems usually rely heavily on solar photovoltaic (PV) systems and Wind Energy Conversion Systems (WECS). However, it appears that due to the relative universal availability and regularity of solar irradiation compared to wind regime, and the fact that wind turbines can be noisy and more difficult to install in residential areas, solar photovoltaics are the heavily-preferred technology among the two. There are also microgrids such as the Mpeketoni microgrid in Kenya which is fueled by diesel, despite the availability of geothermal potential in the region.

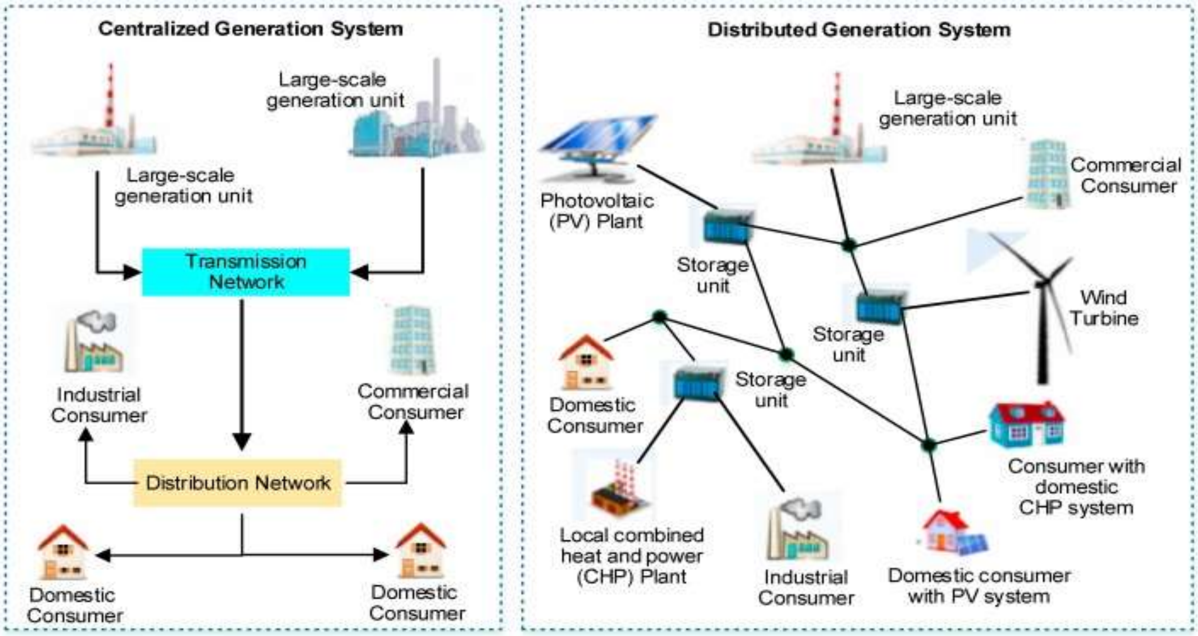

Fig. 4: Traditional Generation (left) versus Distributed Generation (right) [27].

Microgrids have been found to be beneficial especially when introduced in locations with previously limited access to electricity. In the Mpeketoni case, it was found that agricultural activities were enhanced due to increased availability of welding services for maintenance of farm machinery and there was a notable boost in Small and Medium Enterprises' revenues in the region[28]. As such, microgrids are a very attractive option for improving electricity access in African nations but are also useful in other parts of the world[29], [30]. They are arguably the most convenient and non-disruptive deployment methods for small-, medium-, and frequently large-scale renewable applications. However, there are several challenges that accompany the integration of renewable resources into a grid[5].

It has been reported severally in literature [31], [32], [23], [33], that increasing levels of DG penetration have caused problems such as voltage instabilities, loss of frequency stability, and reduction of ride-through capacity in systems. These are attributable to the reduced mechanical inertia of the generation sources in the system. Large rotating machines with precisely controlled output voltage and frequency characteristics tend to contribute mechanical inertia that mitigate the aforementioned problems, but solid-state converter-based technologies such as solar PV, and wind energy systems do not have such intrinsic properties[5].

Curtailment is a situation in which facilities are constrained to produce significantly less energy than they are capable of producing, and this frequently occurs because of the need to limit the instability introduced into the grid by the presence of wind and solar photovoltaic generation resources[34]. The voltage regulation capability of local points of connection are especially affected, to the extent that some authors have postulated the emergence of a reactive power market sole to address such issues[26]. The economic viability of this needs to be further considered in each geographical location, however.

In Europe, as a case study, it was found that electricity utility companies were, at least initially, economically affected by the rapid penetration of renewable technologies as their nature is not highly compatible with the traditional energy market structure[26][35].

3. RENEWABLE ENERGY FLEXIBILITY CONSTRAINTS

The impact of renewable energy penetration on generation systems has been categorized by authors into three concepts, based on the timescale: stability, flexibility, and adequacy. However, the terms are sometimes used interchangeably[36]. Stability is considered to be related to the power quality on a timescale of less than one second, flexibility is considered to cover a timescale of minutes to months, while adequacy refers to long term (multi-year) functioning of the grid[36].

4. IMPACTS OF VARIOUS TECHNOLOGIES

4.1. Solar PV

Solar Photovoltaic is one of the two most popular choices of renewable energy technology for renewable energy-based distributed generation, mainly because of the relative ubiquity of the sun’s energy resource and the falling costs of the technology over time, coupled with the fact that it is noiseless to operate [37]–[40]. Also, installation requirements are relatively unobtrusive and easy to accommodate, with PV panels snugly fitting onto existing rooftops. In addition, from the purchaser’s end, solar PV is relatively immune to or even benefits from economies of scale, making it almost equally as cost effective in small arrays as in large ones [41], [42].

Photovoltaic energy generation systems rely on semiconductors to harness the energy from the sun by the photoelectric effect, which means that they have no inbuilt mechanical inertia, and are also intermittent because the solar radiation is unavailable at night and variable during the day [43]. In AC microgrids/DG systems, solar PV also has to be inverted before being fed to the grid, which means that power electronics such as inverters are introduced as an additional interface on the supply side[44]. These power electronics introduce harmonic distortion into the grid and have numerous negative effects such as overloading of neutral conductors, increased losses, damage to sensitive electronic devices in consumer applications, and difficulties with connected transformers, machines, and other equipment, as well as difficulties with measurement, protection, and control on the grid [45]–[47]. In addition, reliability analysis and evaluation become more complicated [48]. Fig. 5 shows the undesirable effect of increased PV penetration on local voltage stability on a grid as investigated by [49]. These factors interact with each other to give energy losses in the system [50].

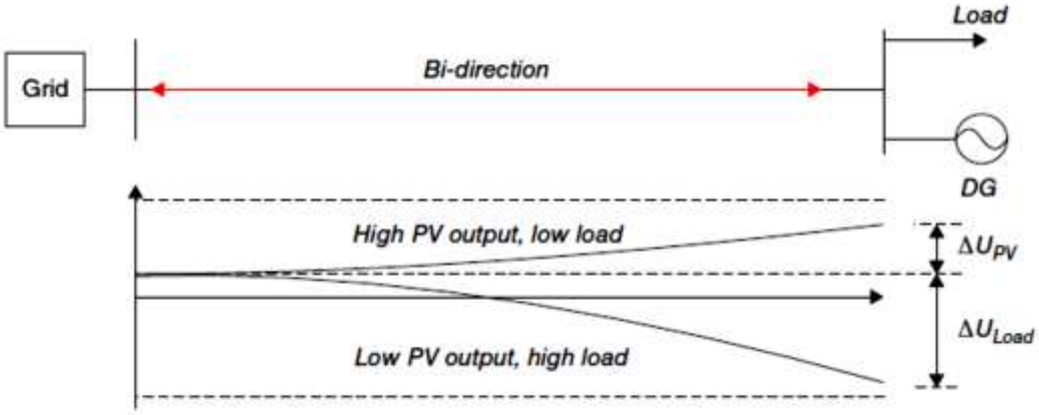

Fig. 5. Impact of Increased PV penetration on the local voltage in DG system [49].

4.2. Wind Energy

Wind turbines have been installed onshore and offshore in increasing amounts of capacity over the years, and have now become the globally-dominant renewable technology in use in terms of installed capacity [51], [52]. Wind farms are known to cause sound pollution in many cases when deployed on land [53]. However, this is offset by the fact that they are unique, in the sense that they can be conveniently sited offshore in large quantities due to the abundance of wind resource over the sea [54]. Compared to solar energy, wind farms benefit directly from economies of scale, such that bigger arrays of bigger turbines have significantly more power output than smaller ones due to the cubic relationship between wind speed and power extracted [55]. However, wind is not as ubiquitous as solar PV (in terms of number of locations) because of its less-convenient installation requirements and ubiquity of wind resource as compared to solar resource.

Wind energy systems can generate both AC and DC power and also rely on electromagnetic energy conversion processes, which, for AC microgrid applications, are superior to solar PV in that respect. However, the wind resource is even more intermittent and unpredictable than solar resource in most locations. This means that in most practical systems, wind turbine output is not connected directly to the grid but is served to the grid through buffer systems that often involve multiple stages of power processing and storage, and thus the rotational inertial advantage that would ordinarily come from an alternator-based source is lost. Fig. 6 shows the structure of a typical wind energy conversion system with multiple power processing stages: rectification, storage, and re-inversion.

Sub-synchronous Resonance is also a phenomenon that is ordinarily rare, but is now recognized as a low-probability but catastrophic failure mode of wind energy systems connected to series-compensated transmission lines, especially with doubly-fed induction generators [56], [57]. This occurs due to cyclical exchanges of energy in power systems with series compensation. When this happens low frequency oscillations are produced that can lead to mechanical damage in the equipment in wind farms.

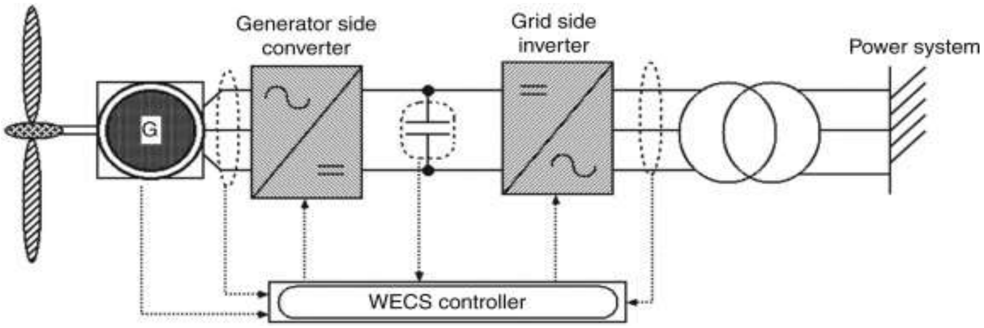

Fig. 6: Wind Energy Conversion System [58]

5. POTENTIALS FOR MINIMISING THE IMPACT OF RENEWABLE ENERGY PENETRATION ON THE GRID

A significant proportion of the negative impact of renewable energy penetration arises from the fact that systems with less rotational inertia reserves (i.e supply from synchronous generators and other massive rotating equipment) and higher proportion of converter-based sources are inherently less stable. Thus, a number of proposed and existing solutions deal with mitigating the impact of these properties on the system. Given that the problems are similar, the solutions are also similar for the different renewable energy types. PV and wind, in this respect, are representative of other electronics-based and alternator-based renewable energy technologies respectively. Many of these solutions have been investigated by researchers and show promise in impact mitigation of renewable technologies on power system performance.

1. **Flywheel Energy Storage Systems (FESS):** A flywheel is a large rotational mass that can stores energy in kinetic form. Flywheels are relatively cheap to develop and install and safety concerns can be addressed by installing them underground whereby they are not able to do much damage in case of mechanical failure. Flywheels are known to be far more durable than batteries due to the fact that batteries are chemical while flywheels are mechanical. Flywheels naturally lend themselves to being fitted into wind energy conversion systems[59]. Fig. 7 shows the topology of a typical FESS.

In the case of photovoltaic systems, flywheels can probably be used as mechanical stabilisation systems such that some of the PV energy can be used to accelerate flywheels by DC motors, or even by combined electricity and heating systems which is analogical to the use of capacitors to stabilise voltages. This way, even if the sun fades temporarily, the flywheel continues to release its stored energy into the microgrid, providing rotational inertia and contributing to ride-through capacity.

This could be used in hybrid configuration with a battery system thereby minimising the proportion of inverter-sourced power in the grid and enhancing stability. This is however subject to further investigation and research to ascertain the efficiency of such concept.

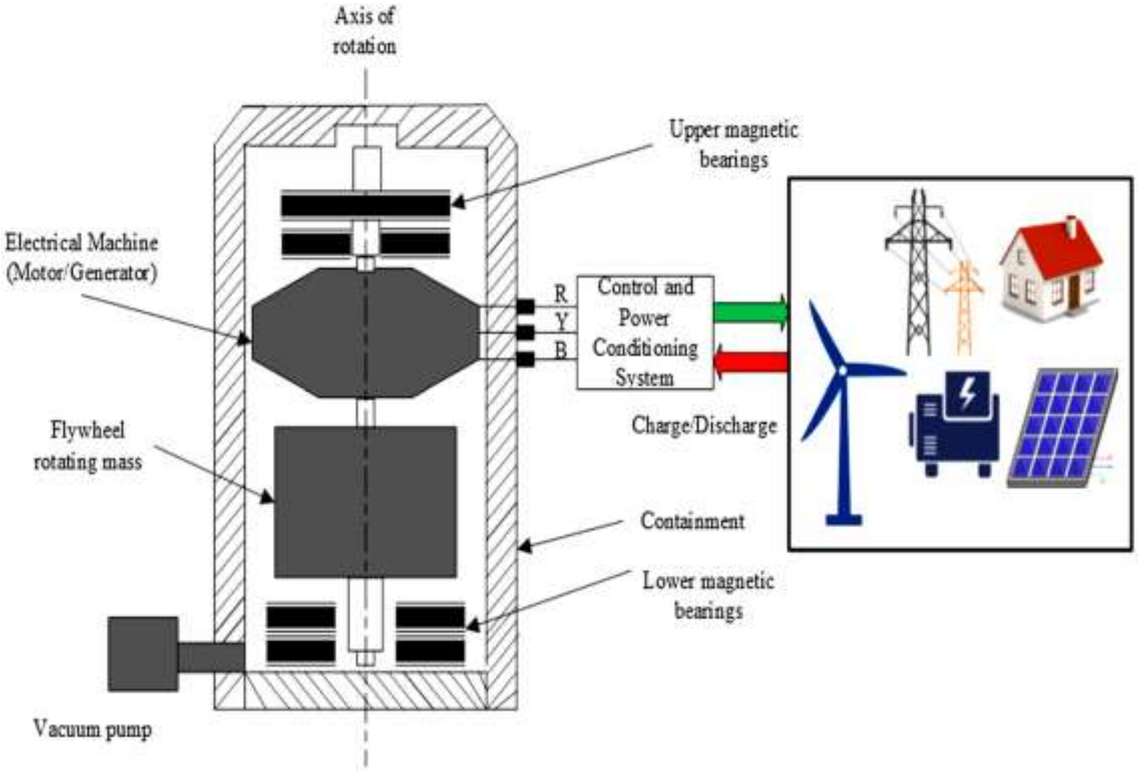

Fig. 7: Flywheel Energy Storage System [60]

2. Pumped-Hydro Storage Systems (PSH): Pumped-hydro storage systems are known to be an option where natural water sources do not provide enough mass flow rate and pressure differential for impoundment hydropower systems. Pumped-hydro storage systems are especially known for their tendency to improve system flexibility[31][61]. It also provides rotational inertia and is almost ideal for responding to rapidly fluctuating power demands.

System flexibility and frequency stability would be significantly enhanced if a portion of generation from PV arrays and wind farms could be efficiently combined with pumped-hydro storage systems such that instead of solely relying on chemical batteries, the pumped-hydro systems can dispense electricity with some level of rotational reserve while retaining high levels of flexibility for response to demands. This is also subject to further research into ways to improve the economic viability and hence public attractiveness of the concept. Fig. 8 shows the structure of a typical PSH system.

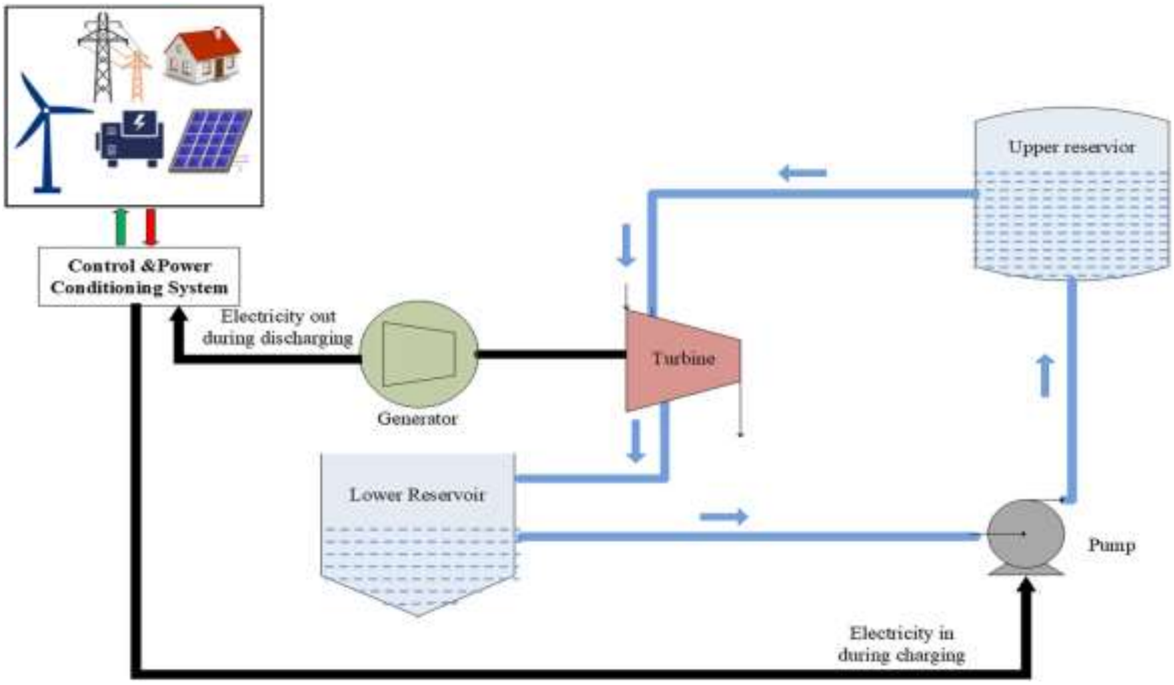

Fig. 8: Pumped Storage Hydropower System [60]

3. Grid-Forming Inverters: A grid with high penetration of distributed-generation, non-rotating renewable sources and may contain thousands or millions of inverters, which introduces technical complexity into the system[15]. The use of grid-forming inverters provides the opportunity for finer control of the inverters. Thus, for DG resources, the use of grid-forming inverters over grid-following inverters should be encouraged.

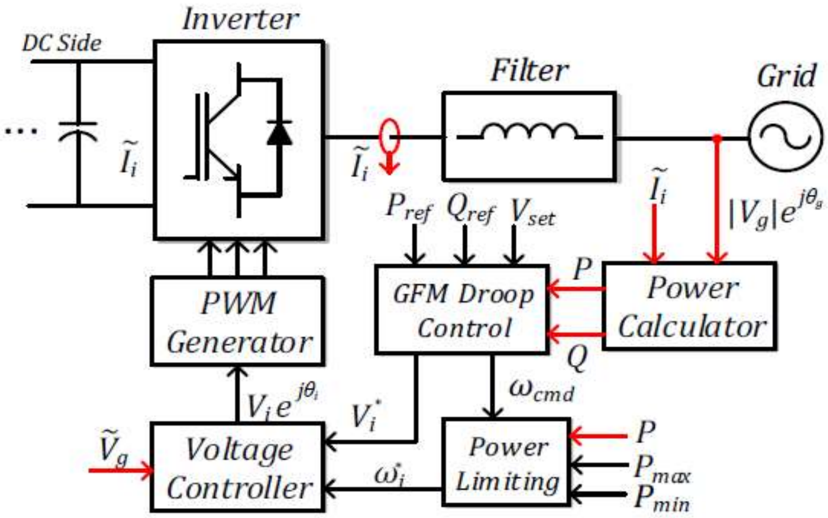

Fig. 9: Block Diagram of a Grid-Forming Inverter [15]

4. Incentivisation of Electric Utilities: Improvements can be made to grid stability by properly-motivated electric utilities. They can be rewarded for the operation of systems that provide good ramping ability, voltage support, inertial response, and fast frequency response. This will motivate them to operate more balanced systems, and to develop and install solutions that improve system stability with high renewable energy penetration.

5. Demand Side Management Strategies: Demand dispatch could be enhanced in the age of communicating devices by an approach to pricing and metering that encourages customers to consume more energy in off-peak periods and less during peak periods[55]. This could be by means of a meter that shows the price of energy at any given time, just like the stock prices. A customer could look at the price and decide to postpone his/her laundry to save a little cost. Such measures will tend to reduce unpredictability of power demand and reduce the consequences of high renewables' penetration. Optimisation strategies such as Pareto frontier techniques could be useful in setting the prices throughout the day so as to minimise the discomfort factor.

6. Synchronverter: The synchronverter is a type of inverter that mimics synchronous generators by electronically simulating inertia in the inverter output, such that frequency drop in the grid supply is mitigated using digital signal processing and control systems [62], [63].

6. FUTURE TRENDS OF RESEARCH IN RENEWABLE ENERGY GRID INTEGRATION

Economic, safe, and reliable energy storage is potentially the most-important issue in mitigating the impact of renewable energy integration on the grid. Of the various classes of technologies available, mechanical energy storage systems provide rotational inertia and higher levels of chemical safety[64], [65]. Of these, the flywheel energy storage systems are the least location-specific. However, the storage capacities of flywheels for grid usage are limited by the strength of the materials used in their construction, and flywheel failure tends to be an explosive, dangerous event[66]. Due to this, composite materials that have high tensile strength ability to withstand vibrations, and can be manufactured in large amounts are been researched and the state of the art continues to evolve. The stronger the materials, the bigger the capacity of flywheels that can be made out of them[67]. Also, flywheel control systems and topologies for renewable energy systems have much potential to be improved with state-of-the-art technologies, such as neural controllers for multi-machine systems[68].

In addition, research into easily-producible arrangements for other mechanical storage schemes such as compressed air energy storage and pumped hydro storage systems, as well as hybridisation of energy storage technologies has shown potentials for powerful solutions towards improving the economic competitiveness of energy storage systems[65].

Furthermore, systems with major proportions of DC infrastructure, such as AC/DC hybrid microgrids, have challenges that frequently call for different solutions from those established for use in AC-dominated systems such as achieving the optimal load flow, power system protection, and grid-control topologies[69]–[73]. Thus, DC microgrid research continues to grow in importance.

7. CONCLUSION

Renewable energy and their derivative microgrids have been a positive addition to the energy mix in countries within and outside Africa. The main challenge that comes with increasing renewable penetration, however is the detriment to the grid performance owing to their lack of inertia, as well as their economic disruptiveness. This can however be mitigated by applying a number of technical and economic measures in the design approach to the modern grid architecture, such as introduction of rotating inertia into the generation system where economically possible, using such techniques as pumped-hydro storage and flywheel energy storage, while also generally sticking to the use of grid-forming inverters, and implementation of demand management strategies leveraging communication technology.

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