Renewable Energy Integration in Smart Grids: A Review of Recent Solutions to a Multidimensional Problem

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Abstract - *This paper is a survey done about integration of renewable energy systems into the Smart Grid. It looks at the most important challenges that arise with this topic, and at the latest solutions deployed to overcome them. This survey provides a review of the problem from different perspectives, and highlights several selected solutions, presented as best practices. Some of the main issues discussed relate to the intermittence of renewable energy, grid stability, and reliability issues.*

Key Words: **Renewable energy, Smart grid, Synchronverter, Machine learning, Data Analytics**

1.INTRODUCTION

As the world and technology advance towards more efficient energy resources, and as climate change becomes an ever-increasing issue of concern, more attention is paid to the advancement of renewable energy, and its integration into the grid. The grid needs to be intelligent enough to adapt to this addition, while also accommodate high load dynamics from electrification of processes, also known as the smart grid. As the topic of renewable energy grid integration is quite dynamic, and as more scientific achievements find solutions to the challenge of RE grid integration, this survey paper provides an overview of the recent publications in the past five years, highlighting the most important issues facing the integration of clean energy into the grid, followed by the latest technologies and strategies deployed to overcome these challenges, including some best practice examples.

2. MOST PREVALENT ISSUES IN RE GRID INTEGRATION, AND SELECTED SOLUTIONS

Environmental benefits of using RE on the wide scale are well known, in terms of reducing carbon emissions and bringing global warming to a halt, but the benefits go beyond the environmental scope. In fact, there is a positive social impact for electricity users who become more energy independent, and create an income by producing their own energy locally and then selling it as well. Moreover, having this new area in the market creates new opportunities and more jobs, so the benefits fall in the economic aspect as well. [1]—[3] There is no doubt that integrating RE into the market is highly desirable, but before that, there are quite a few issues that need to be resolved before that becomes possible.

A survey done on the latest papers published in the past five years including 2021, highlights certain prevalent issues in smart grid integration, which are repeated in different case studies across the globe. Scientists and researchers have found various ways to tackle these issues and further enhance the smart grid by optimizing the use of renewable energy sources. The next section provides a closer look at some of these issues and proposed solutions.

2.1 Intermittence of RE Systems

"The sun doesn't always shine, and the wind doesn't always blow". Renewable Energy sources such as wind and solar are variable in nature both in short and long term. This is the most common problem, that was found in many of the papers, and it is also the root cause of further issues discussed later. [4] — [11]

The main solution to the intermittent nature of renewable energy systems in the short term is energy storage. This is not just confined to Battery Energy Storage Systems (BESS), which can be inefficient and environmentally harmful, but also include mechanical energy storage, such as pumped hydro and compressed air energy systems (CAES). [4] Another concept to consider that could solve the intermittence issue is Energy Cooperation, and this innovative method allows energy exchange and sharing, and reduces the need for energy storage systems. This energy management system is optimized for a couple of microgrids sourced with RE. An offline optimization was first developed, and then a simpler online optimization was further developed from it. Moreover, the optimization was applied to two such microgrids in Tucson, Arizona, USA, and further extended and evolved. [11]

Looking from a different perspective, having such a volatile energy source makes it necessary to have precise power forecasting, to facilitate planning and designing power systems. Data Analytics is a strong tool that utilizes statistics and machine learning to create a model, which has to be trained using real data for accurate results. This data usually needs to be pre-processed before being used to train the model, and was in fact done so through software such as Python which additionally has a library for solar PV (PVLIB). [5]

2.2 Grid Voltage and Frequency Instability

RE sources cause grid voltage and frequency instability, and this is another highly common issue that urgently needs to be addressed, and in fact was addressed in various ways. [7] [8][10] [12] — [15]

One method to regulate the voltage is through controlling the BESS, to limit the voltage rise during peak generation, and voltage drop during peak load. In paper [14], M. Zeraati et al. developed two algorithms, one related to the installed capacity, and the second involving the battery's SOC (State of Charge). The different operating conditions were studied using Matlab and Simulink. [14]

2.2.1 Harmonics

Frequency instability also means having harmonic distortion, and oscillations which are harmful to the grid. [8][9][15]

Measuring the level of this distortion, also known as THD, or Total Harmonic Distortion, is an ideal way to begin solving this problem, and helps to develop a solution for it. This was done on a distribution network with a PV plant integrated to it, which was modelled to evaluate the level of THD at different PV penetration levels. The results indicated the increase in THD with more PV integration. [15]

A novel solution presented to solve the issue of grid instability, is through implementing an Electric Spring. An electric spring, which takes Hooke's law into the electric domain, can control voltage changes on sensitive loads, and this device is here utilized to stabilize the voltage on the load side, to follow the source voltage for a PV system, with MPPT (Maximum Power Point Tracking) as well. This resulted in better performance than other more typical solutions such as capacitor banks, and static compensators. [12]

Another solution presented is through peak shaving, through taking advantage of loads that are flexible in times of usage, such as Electric Vehicles (EVs). This is further illustrated in the work of Acharige et al. [13], in which solar PV is connected to a smart EV charging system, to allow V2G (Vehicle-to-grid) inputs, where EVs can supply the grid, both solving the intermittence issue, and also enhancing grid stability. Method Used: A bidirectional DC-DC Converter (including MPPT) is designed and simulated, which allows the EV battery to be charged by the solar PV, or discharged into the grid, thereby protecting it from the high variability of solar energy and enhancing its stability.

Furthermore, an inverter has to be used when connecting RE sources to the grid, to facilitate system stability and control, and inverters can be complex and costly, so an example of overcoming this was through a new design of a Multi-level inverter (MLI), as shown in Figure 1 which is less costly, and requires less components. Moreover, it follows standards, and has an improved performance at high output energies, when compared with other inverter designs. The design was verified using Matlab & Simulink. [9]

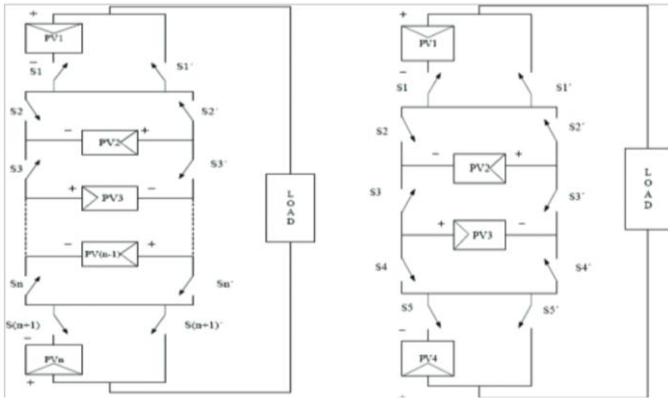

Fig -1: Circuit diagram of the proposed MLI (left) and a 15-level MLI example (right) [9]

Another solution was presented, on a large scale and real-life example, in Zhangbei, China. [10] This was a way to improve stability on the large scale, for grid transmission, as can be seen in the Voltage Sourced Converter based High-Voltage Direct Current (VSCHVDC) used for transmission of RE as can be seen in Figure 2. The figure shows the different grid interconnections, including two lines for RE power stations, a line joining an energy storage system, and a line for the main consumption terminal. The controller performance of the VSC-HVDC was optimized to improve the transmission's stability. This was done through modifying the proportional gain in the outer feedback loop, and also through using a circulating current suppressor. This achieved a reduction in the risk of oscillations that come with RE grid integration. [10]

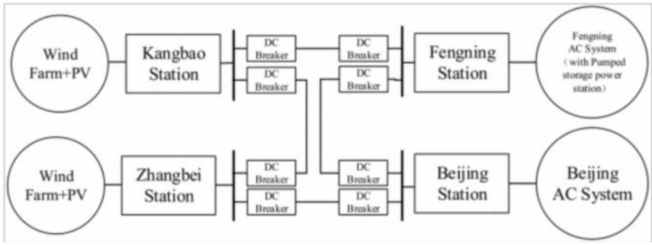

Fig -2: Structure of the Zhangbei project [10]

2.3 Risk of Power Imbalances, Low Reliability

The intermittent nature of renewable energy causes high power imbalances, [13] [8][11], and this also means low reliability, and more blackouts. [16] [14]

Integrating RE into the grid and being able to smoothly switch from conventional to non-conventional power supply needs control. Such a control system has been simulated, designed, and further analyzed though Matlab and Simulink, with results showing the effectiveness of the system in both a normal operation and during faults. This resulted in a self-healing system, with automated fault restoration. [16]

2.4 Low System Inertia

Most RE systems such as solar PV, and wind energy systems have no heavy rotating masses connected to generators, meaning they have a low system inertia and small power tolerances, furthering the issue of instability and unreliability. [4][17] [8]

A way to overcome low system inertia is through using a synchronverter, which is an inverter that mimics a synchronous generator, as demonstrated in the work of Hou et al. [17], through a synchronverter used in a grid-connected solar PV system, where a novel fuzzy logic controller (FLC), was developed to manage the system, and the key here is the controller, which resulted in having a quick response, and increased system stability.

2.5 RE Integration is Still Relatively New

Renewable energy integration in smart grids is still not mature enough, and there is not much system understanding for planning and operation. [6] [7][18]

The capacities of RE systems such as wind and solar can be found through various software, including Matlab, for power flow calculation and stability analysis. [6]

Identifying points to be improved, and current system limitations is the way forward. The capacity of an RE system does not just depend on the amount of energy production, since the fluctuating nature of renewables leads to stability issues that the grid might not be able to handle, and so the energy output is curtailed, and the actual capacity might be a lot less than expected. That's why it's important to accurately size the system, as was done in [7], using the Effective Short Circuit Ratio (ESCR), in Tibet. The ESCR is an indicator of the power system's strength. The results highlighted the weakness of the grid in Tibet, as shown in Figure 3, which shows that the connected capacity falls much less than the estimated capacity. Despite having a high amount of solar resources, the actual usable capacity has been limited by the system's weakness. [7]

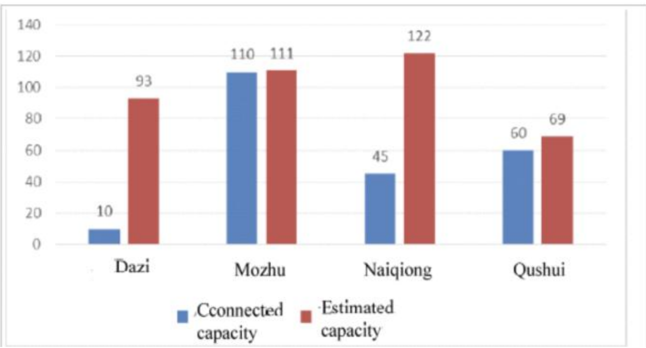

Fig -3: Grid connected capacity vs estimated capacity [7]

Another interesting take that utilizes the existing grid infrastructure, and introduces RE sources to it, is a hybrid of nuclear energy and RE energy, that was modelled with a specific load, and system components, and optimized using HOMER (Hybrid Optimization of Multiple Energy Resources). The best model found was a grid connected nuclear-RE micro hybrid energy system. [18].

2.5.1 Lacking Standardization

Having a new system also means there is still not enough standardization over the components, systems, and connections. [3] [19]

Developing and following local and international standards, especially at the beginning stage of a new system, is a necessary action to take. This requires a lot of testing to be done on the new devices to ensure their compliance, which usually has to be done manually, and is time consuming, prone to errors, and inefficient. A new way to facilitate this testing was done through the development of a grid integration test platform for RE smart grid penetration. This standardized and automated the testing process, through utilizing simulators for solar PV, batteries, grid, and developing an integrated test procedure, resulted in an 85% time reduction of the overall testing process, as can be seen in the Figure 4, and achieved consistency, interoperability, and ensured personnel safety. [19]

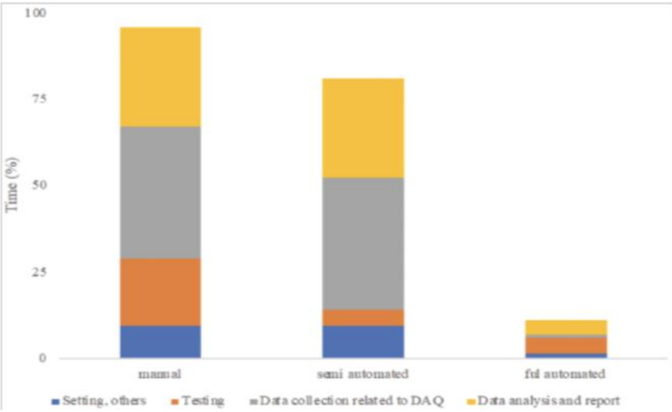

Fig -4: Time reduction with the automated testing platform [19]

2.5.2 Cost Estimation Challenges

Low system understanding also means it's difficult to quantify the cost of grid improvements due to the addition of clean energy into the system. [20]

The cost estimation was done on a large scale for San Diego Gas and Electric, where yearly expenditure costs were related to the amount of installed VRE (Variable Renewable Energy) capacities. [20]

3. CONCLUSION

Integrating RE into the grid is a multidimensional problem, and electric power specialists, along with experts in many relevant fields investigate to solve different aspects of the problem. It was noticed that control was a prevalent issue, along with other topics such as protection and optimization. Moreover, a significant number of the presented solutions and designs utilized Matlab and Simulink, along with other software such as Python, HOMER, etc., indicating the ever-increasing importance of simulation software for finding advanced solutions. Furthermore, it was also noticed that these recent solutions were not just deployed in developed countries, but also many case studies were used in developing countries as well. Finally, although there is still a long way to go before achieving a full transition into renewable, it seems the path ahead is clear in terms of areas of improvement, and required objectives that would push the smart grid to the next level.

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BIOGRAPHIES

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