Distributed Generation Integration into Grid

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According to [25], DGs could also be defined as a small source of power production for storage (usually within the range of less than a kW and tens of MW), which is not a portion of the huge, centralized power network and is located close to the load. Another school of thought defines DGs as power pockets usually located near consumers, which have a relatively small capacity of 30 MW or less, with the ability to economically support the distribution grid. This description involves DG technologies such as photovoltaic systems, concentrating solar power, micro turbines, reciprocating engines and fuel cells.

grid integration | grid planning | harmonics | optimal capacity | penetration levels | power network

1. Introduction

The quantity of power that is fed into the electricity network from distributed generating plants could potentially pose challenges for power system operators. These challenges range from voltage fluctuation and reverse power flow to overheating of components. The increased inflow of electrical energy into the power network necessitates significant grid reinforcement, especially in distribution networks where voltage stability is imperative. The push factors behind the increasing renewable energy (RE) penetration levels include reliability, security, advances in technology, regulatory issues and emission reduction concerns. Moreover, increasing competition in the electricity market, issues of obsolete grid equipment and capacity limitations have driven the adoption of distributed generation (DG) technologies as part of the new power systems to resolve these challenges [1]. In the current deregulated electricity sector, investors are usually skeptical in making investment decisions on power projects that involve huge amounts due to extremely long payback periods. These factors, and the deregulation/decentralization of the electricity sector, together with the growing global electricity consumption, have made DG technologies a sustainable power supply option for the near future [2].

Grid capacity expansion by means of integrating distributed renewable energy systems has become an emerging global trend, likely to have a significant impact as a result of a drop in the cost of renewable energy system accessories such as solar PV, biomass and wind energy [3]. Recently, there has been a transformative evolution in the electricity grid and industrialized countries such as Germany and Denmark are making enormous progress in increasing the share of distributed renewable energy systems in their total energy generation mix. Germany is leading the race in grid expansion and renewable energy integration, greatly favored by the implementation of feed-in tariffs in 1990 [4], which led to the installation of 92 GW capacity from solar photovoltaics, wind and biomass systems in the last quarter of 2015. Their counterparts from developing countries are still reluctant in adopting this scheme due to the technical and financial implications involved, but they have, however, expressed a desire to increase renewable energy shares in their energy production mix, as could be justified by the content of their Nationally Determined Contributions (NDCs). They have adapted their regulatory frameworks to encourage these technologies and their energy sector could experience similar progress as Germany. To efficiently integrate distributed generators into the grid, the flexible infrastructure of power electronic converters with customary tasks for power quality and conditioning are required [5]. In electricity grids dominated by distributed renewable energy systems, high grid overload may occur due to the increase in power generation from the distributed renewable energy systems not matched by increasing power demand [6]. Consequently, strategies to regulate load flow need to be focused on either monitoring consumers or the curtailment of distributed generators.

The achievement of conveniently high renewable penetration levels in the grid could be easily done through a smart grid system. This system has the ability of monitoring the power system network for overloads and intelligently rerouting the electrical energy to avoid a potential power outage. Kempener et al. [7] suggested that it is economically feasible to use smart grids over conventional systems when considering renewable injection in the grid and any grid optimization needs. The literature on this subject has identified three unique levels of renewable penetration, namely low, medium and high, which are classified in line with the kind of grid reforms required to accommodate renewable energy. Many researchers have conducted studies on renewable energy systems' (RES) integration into the grid with emphasis on various aspects. In a study conducted by Muntathir A.T. and Chokri A.B. [8] on the optimum placement and penetration levels of photovoltaic (PV) systems on an IEEE 30-bus system using the Electrical Transient Analysis Program (ETAP), they reported a 50% penetration level and concluded that this amount was satisfactory. Zahedi [9] studied aspects relating to the push factors, merits and challenges of distributed renewable energy integration into the grid and the end user perception issues were predominant. Luhmann T. et al. [6] suggested a method of managing increased solar–wind–biomass capacity in the distribution grids in Northern Germany using low-cost solutions. They developed a medium-voltage (MV) grid model where several scenarios were simulated and assessed using a 5% load flow-dependent energy curtailment approach. They concluded that the 5% approach was a promising structure for reducing the costs of renewable energy integration into the distribution grids.

The obtainable scientific information mainly focuses on general issues influencing the interconnection of distributed energy sources into the power grid [9][10][11]. Other authors have studied particular issues (voltage fluctuation, reverse power flow, power losses) affecting power injection into the grid using ideal test grids, with little coverage of how these issues may actually differ in a real-life grid system [8][12][13][14][15]. The authors in [16] have suggested some performance indicators to evaluate the benefits of DG units, focusing on voltage profile enhancement, lowering transmission line losses and reducing environmental impact. Similar studies using technical indicators were conducted by [17][18] with the addition of line capacity. However, there exists a gap in the literature regarding how some of these concerns have affected real-life power systems and how the situation is currently being managed by system operators. Learning from case studies and empirical experiences is important to ensure that grid management strategies are effective and practical to deploy at a large scale. As a contribution, the study constitutes a curious attempt to provide a scrutiny of the complexities of interconnecting renewables into the electricity grids and markets. It offers informed viewpoints on the issues and solutions resulting from proven best practices used by power system operators and electricity markets across a few successful countries across the globe. The study emphasizes the practical application of methods in the real-world setting with theoretical foundations and empowers the improvement of supportive policies. It deliberates on renewable energy integration issues, hence making sure that grid operators with insignificant renewable penetration levels can learn from the successes accomplished by their peers.

2. Some Practical Options Used in DG to Grid Integration

At the level of the substation, HV/MV transformers adapted with voltage regulation functionality are used to adjust the voltages in the transition between the HV/MV networks [19]. Most utilities in the past used voltage regulators mainly as an intervention mechanism to compensate for voltage fluctuations on the HV network and stabilize the MV to a fairly constant level. With the advent of renewable energy integration in the grid, power system operators in Germany [19] have incorporated power electronics and software applications in order to adjust MV levels with respect to the percentage of renewable energy penetration and the load flow situation at the substation. This is done to subdue the increasing voltage on the MV network in situations of renewable injection. However, this approach has a number of challenges. For instance, voltage variation could negatively affect commercial manufacturing plants connected to the power network at the medium-voltage (MV) level, which limits the widespread application of the dynamic voltage control. Moreover, the possibility of reducing the voltage in a network will depend on the physical spread of the renewable energy systems in a given MV grid area, such that energy systems that are far from the substation could present problems when reducing the voltage. Nonetheless, the application of this method is viewed by the German Distributed System operators as one of the most cost-effective procedures to increase the hosting capacity of the grid [19].

Actions geared towards the reduction of grid impedance would improve on the hosting capacity of renewables in the power network. A practical approach often used by German system operators to reduce grid impedance is the closed-loop application in MV networks [19], where a radial MV grid configuration is transformed into closed rings where each substation is connected to more than one energy supply line. This approach connects previously autonomous transmission lines that were fed by a common distribution transformer to a switching station, thereby creating a closed loop. However, this method makes the detection of faults and fault recovery very difficult and the approach remains controversial among power system operators. Therefore, sustainable methods that evenly distribute injected renewable power into the entire grid need to be developed for optimum utilization of the existing grid capacity.

Another technique used by system operators to increase the penetration level of renewables is by establishing renewable energy generators to serve as a backup, such that, when there is a fault in one part of the grid, the backup supplies the grid. Renewable energy systems can be continuously added to the grid as required by the energy demand and grid stability, but they could become detached if the stability of the network is compromised. A power substation could be equipped with an additional HV/MV transformer that helps to support the network during either system maintenance or other contingency events. This transformer could be used to host more renewable energy systems in the given MV network. While this method would improve the utilization of the available grid capacity, it, however, renders power system operation more complex [19]. Simpler methods must be developed with clear implementation guidelines and protection measures so that renewable energy systems can be conveniently added to the grid in an incremental manner.

Since the injection of active power in the grid causes a voltage rise, the ability of distributed renewable energy systems to generate reactive power is used by system operators to control the voltage quality. The injection of reactive power neutralizes the voltage rise, thus improving the ability of the network to host the renewable energy system [19]. Advanced methods such as automatic supervisory control systems to regulate reactive power injection have been used by system operators at the HV level. The control of reactive power can also be used to smooth the reactive power imbalance in the MV network, which is usually supplied by generators.

3. Issues Resulting from DG to Grid Integration

As seen in the power loss equation, current is a function of the power flow in the lines and any changes in power flow affect the losses in the line. The amount of loss incurred in a power system as a result of DG integration will depend on the quantity of electrical energy injected and the connection point of the DG to the grid. When DGs are connected to loads in a distribution feeder, the energy supplied by the DG will be directly utilized by the electrical appliances and this reduces the flow of power as well as losses in the feeder. Moreover, the flow of power from the main grid (HV/MV network) to the load is reduced and the risk of grid overloading is minimized (advantage of DG integration) [20]. In a situation where the energy supplied by DGs into the distribution network is more than the conductors were initially designed to accommodate, there will be increase in power losses in the network. The cumulative effect of power losses can significantly affect the cost of managing the network, and, most often, this cost is shifted to consumers through increased tariffs.

Distributed renewable systems such as wind turbines, which have power electronic components such as inverters, at some point in the energy conversion process, may introduce current harmonics accompanied by voltage distortion [5]. The order and magnitude of the current harmonics will greatly depend on the type of converter, inverter characteristics and the mode of operation. Nonetheless, most recent inverters connecting DGs to the power network have the ability to actively shape their current output to an acceptable limit, although some of the injected harmonic currents can distort the voltage profile, which can spread throughout the entire grid [21][22]. For wind turbines that have induction generators incorporated, there may be the occurrence of harmonics within a short time interval at startup, caused by a power electronic device. Some loads could also be a source of harmonics, where they introduce unwanted frequencies into the power grid in multiples of 50 or 60 Hz, and this could cause the power system to malfunction [15]. In summary, the presence of harmonics in a grid gives rise to diverse issues including temperature rise in the equipment, a drop in the power factor of power system components, a reduction in the performance of electrical devices, faulty responses of protective devices, communication signal interference, failure of neighboring equipment through resonance, noise, undesired vibration of electrical motors, etc. [13].

In the past, power networks were radial, with a unidirectional flow of power, and grid operators interconnected DGs in a ‘fit and forget’ style. However, greater power penetration from the DG became problematic as the injected power reached unacceptable levels. When connected to the grid, the DG displaces a substantial quantity of power from the main grid, which affects the dynamics of power system operation. The idea of a change in the dynamics of grid operation is also supported by [23], where the authors argue that the grid will be exposed to system instability, especially for a DG power penetration level of over 30%, in a situation where the DG unit replaces a major conventional generator in the main grid, causing a drop in the existing inertia in the grid. However, the penetration level greatly depends on the limits of the grid.

Thermal overload poses a problem to the distribution network via heating as a result of power in the network exceeding the power ratings of the system components [24]. Transformers are one of the most expensive components of the power system and any overloading would cause several collapse mechanisms and sometimes lead to complete damage.

4. Merits of DG Integration into the Grid

Due to the numerous merits of DG on the grid, there is growing interest from countries through their regulations to increase DG interconnection into the grid. The advantages become even greater if the DGs are from renewable sources, where additional merits such as a reduction in emission levels and capital cost of investment on an RE system as compared to conventional fossil fuel-based energy production are observed [8]. Generally, the injection of electricity from DGs (renewable and non-renewable) into the central grid provides numerous benefits, such as minimizing real power losses, voltage stabilization, grid stability, system reliability, peak demand curtailment, harmonic pollution reduction, reactive power support, frequency control and generation cost reduction. The merits are briefly discussed below.

Due to the fact that most DGs are installed near load centers, where the power produced does not have to be conveyed through long transmission, power losses are greatly reduced [25]. Therefore, the power is easily delivered where it is generated so that it does not need to be evacuated from the main grid with high power losses.

When real power is added or reactive power is utilized in the grid, the voltage waveforms and the load factor of the network are improved [20][25]. DGs are capable of providing real power and consuming reactive power and, hence, support the voltage profile and load factor of the network. However, the ability of the DG plant to perform these functions will depend on the connection point and the capacity of the DG plant.

Distributed generation has the potential to reduce customers’ electricity bills and deliver power with improved efficiency [9]. Electricity tariffs usually take into consideration the inefficiencies in the transmission and distribution network, where power losses occur, and this situation is intensified when the transmission distance is long. Hence, distributed generation could make electricity tariffs cheap and affordable since energy will be generated near load centers, but this is not obtainable with a centralized electrical network, where power is transported over a long distance to consumers, incurring huge line losses. In a liberalized energy market, where investors are allowed to install their own DGs, more power could be made available as investors respond to varying market forces; hence, system flexibility and competition would be increased, which could greatly reduce electricity prices.

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