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Challenges & Control Opportunities in the Integration of Solar Energy into the Smart Grid: A Survey

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Abstract

Smart grid is among the most important & ambitious endeavors of our time & smart grid vision demands the integration of different renewable energy (RE) sources in one component. Challenges in the integration are obvious as RE sources are highly variable with respect to many electrical parameters. The smart grid must absorb the variability of these sources through critical technological solutions. The survey reported in this paper deals with the opportunities & the challenges posed by one such major RE source i.e. solar energy in the whole integration process to ensure bidirectional power flow, safety, security & reliability in order to attain the future grid objectives.

1. INTRODUCTION:WHAT ARE SMART GRIDS

Any power system face number of challenges each as new dynamics of future demand and supply, aging infrastructure, complex interconnected grids, demands of consumers and regulators , need to lower the carbon emission , new type of loads, and integration of large number of renewable generating sources. Changing energy system requires new solutions. That is why smart grid came into picture. A smart grid is an electricity network that uses digital and other advance technologies to monitor and manage the transport of electricity from all generating sources to meet the varying electricity demands of end users. Smart grid coordinate the needs and capabilities of generators, grid operators , end users and electricity market stock holders to operate all parts of the system as efficiently as possible, minimizing the cost and environmental impact while maximizing the system stability, resiliency and stability. Smart grids are a set of evolving technologies that will be deployed at different rates at variety of settings depending on local conditions such as existing technologies, regulatory framework and investment framework.

2. RENEWABLE ENERGY INTEGRATION

The increasing energy demand at reduced cost and higher reliability requirement are motivating the existing power systems towards using renewable energy sources as an alternative for the future energy. The advantages of a renewable energy as a fuel are; free and inexhaustible, environmental friendly, silent operation and economically viable.It has a potential to supply a significant rising demand of the energy in a sustainable and renewable manner. Owing to these benefits, distributed RE sources has drawn the attention of utilities, governments, environmental organizations and commercial organizations in India and world [1]. Moreover these are installed near the load centers therefore provides additional advantages such as reduction in transmission lines congestion, reduction in transmission & distribution losses, helps in maintaining the required voltage profile, improves system stability and reliability [2].

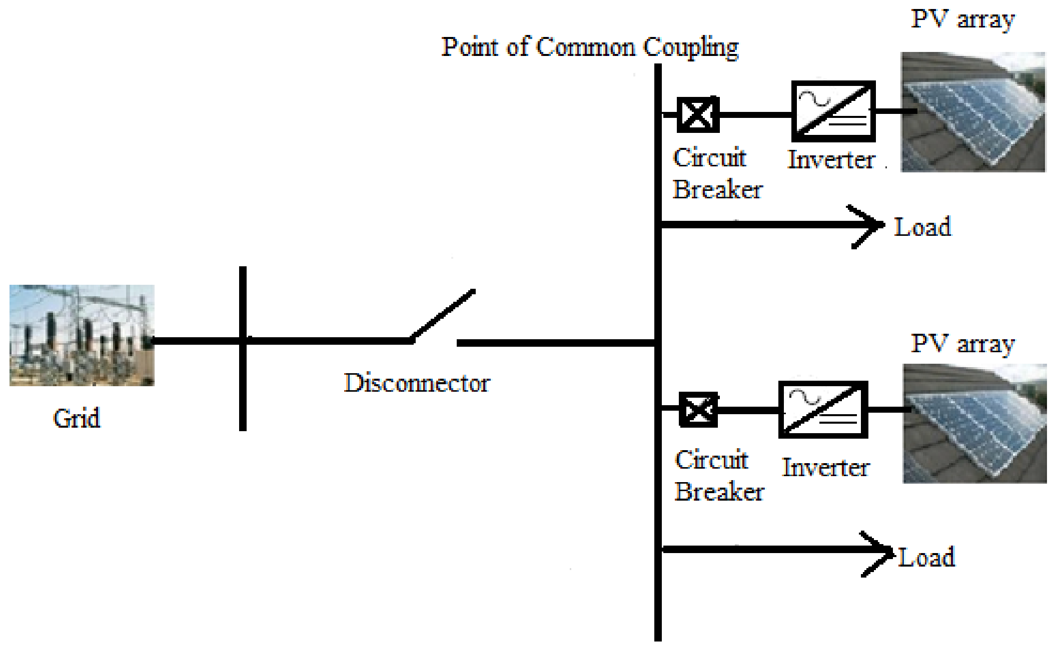

Figure 1: Grid-tied Solar PV System

3. DEALING WITH VARIATIONS

The renewable energy sources are unpredictable and variable in nature. Moreover the distribution grid is not designed to accommodate high penetration of these sources. Therefore such penetration poses the technical challenge like power quality, reverse power flow, voltage variations and the other impacts on the grid which requires the immediate concern of the utilities [2-3]. This paper reports the various challenges and control opportunities (with reference to Figure 1) in the integration of solar PV in future grid infrastructure. Various Issues and challenges associated with high level solar PV integration are provided in references [4-6]. More rigorous issues that need to be addressed are presented in subsequent sections.

3.1 Voltage Rise, Regulation and Unbalance

Change in weather conditions and seasonal variation causes uneven solar irradiation, which produces voltage fluctuations in the output of PV systems. Performances of PV modules also depend on solar irradiance, cell temperature, crystalline structure and the load resistance. Moreover the event of cloudy or Low light situations produce voltage and power fluctuations which affect the network operational performance drastically. The effects of moving cloud results the variations in PV system output have been studied in references [7-8]. Literature also reports the slow and fast voltage regulation due to passage of cloud near PV arrays. These investigations also emphasized on the capacity of the utility generation to respond to the variations in PV system outputs. Impact of abrupt passage of cloud pool over the PV module has been reported in references [9-14]. It has also been reported that such condition affects the output of solar PV at the point of common coupling. Further due to change in environmental condition entire covering of PV array is also likely, which along with unexpected rise in load demand affects the system performance severely. The utilities must be equipped to overcome such situation by supplying reserved energy to the system [9-14]. Woyte et al.; Tan et al. [15-16] reported the passage of cloud over the PV array affects the voltage level and produces voltage fluctuation at the PCC. Kern Jr. et al.; Garrett et al. [12], [17] addressed the effect of cloud transient on the centrally located PV system and examined that the maximum tolerable penetration level of PV was 5%. Bletterie and Pfajfar [18] presented the analysis of the “very-short voltage variations” caused by photovoltaic generation. Long-term measurements are made for a variably cloudy and sunny day at a large PV installation in Austria, it was reported that very short duration voltage variation occurs at PCC owing to irradiance variations. Ari and baghzouz [19] presented the impact of cloud-induced transients on voltage regulation in distribution system with high PV penetration levels. Shalwala and Bleijs [20] investigated the voltage regulation problem due to grid connected PV systems under peak and light load conditions in a residential electricity network in Saudi Arabia. References [21-23] investigated the impact of large PV system to the operation of distribution feeders. The reduction of voltage drop and power system loss was observed with the dispersed PV system for the local loads. Impact of large PV penetration became more significant with higher solar irradiation level and low demand conditions, which increased the feeder voltage and confined the maximum PV penetration to the system in order to maintain the required voltage profile. Chen et al. [24] reported the over and under voltage due to the excess installation of PV at the customer installations. This voltage variation caused the tripping of the protective devices. Pais et al. [25] used the unbalanced three phase load flow analysis to assess the voltage profile of distribution network with solar PV and suggested the solution such as transformer tap changing, PV power factor control and generation curtailment to improve the voltage profile. Nigar et al. [26] examined voltage profile variation and suggested some mitigation measures like storage and generation shedding in order to tackle the voltage rise problem of the system and fully utilize the renewable power generation. Under variable load condition the output of the Solar PV inverters changes in stochastic manner which produces the output voltage of variable magnitude and frequency and creates flicker, this may happens directly due to change in load condition [27-29, 32] or due to frequent change of transformer tapping .The undesirable voltage fluctuation may lead to undue operation of load tap changer which reduces the life expectancy of load tap changer [27, 30, 33]. Such situation also affects the performance of FACTS devices [31]. Small size PV units connected to low voltage grid through single phase inverters produces considerable voltage unbalance on the other hand large centralized PV units connected to medium voltage network do not produces voltage unbalance. Occurrence of voltage unbalance depends on types of inverters and the voltage level at which their output is connected [34-37].

3.2 Harmonics and Power Quality

The problem of power quality in low voltage (LV) connected solar PV arises mainly due to current and voltage imbalance [38]. Harmonic distortion is one of the growing power quality concerns that debase the performance of power system. One of the causes of harmonic distortion in LV grid is increase of power converters and nonlinear loads. Harmonic distortion is also caused by nonlinearity of equipment such as transformer and rotating machines [39]. Harmonic distortion creates excessive power loss, abnormal temperature rise and requires de-rating of the load. In addition harmonic results the overheating of transformer, overheating of neutral conductor and malfunction of protective devices, which jeopardize the stability and reliability of the system. Various standards that address the requirements for the quality of the electric power supply must be carefully analyzed [40]. Solar PV system might introduce harmonics in the distribution network. These harmonics are caused in the conversion of DC to AC power by the inverter. The harmonic order and its magnitude will depend on the power inverter technology, modulation technique, method of commutation and the existence of high or low frequency coupling transformer and interconnection configuration [41-45]. Number of solar PV units connected to grid system and the interaction between grid components and PV units further intensify the harmonic distortion. A harmonic filter is needed between the dc/ac converter and the grid. L, LC, or LCL is the most commonly used filter topology [43, 56-57]. Oliva and Balda [46] presented the study of two PV system connected to the distribution grid through a PWM inverter and reported the malfunction of harmonic-sensitive equipment due to excessive injection of harmonic current in the system. Enslin and Heskes [47] addressed the power quality problems such as higher current and voltage distortion due to; interaction between the distribution network, household capacitance, and large number of inverters; Parallel and series resonance phenomenon between the network and these inverters; and topology of an inverter. Infield et al. [48] reported harmonics problem with their negative impact on distribution system and the possibility of disruption to other customers from multiple grid connected inverters. Valuable approach for the inverter design and control issues was presented in order to improve the power quality. Papaioannou et al. [49] presented the field measurements results of a 20 kW solar PV plant connected to the distribution network with the simulated model. The harmonic behavior of the PV plant as a function of the solar radiation under several weather conditions were analyzed and acceptable penetration level of PV plants was examined without violating the harmonic limits in the network. In medium voltage (MV) network due large penetration of solar PV, Harmonic resonance problem at the interconnection point of the grid was reported [50-51]. Harmonic resonance in grid current and/or voltage occurs at certain frequencies due to the interaction between grid and inverter output impedance. The effect of harmonic resonance presents the tripping of sensitive equipment [50]. In [52-53] various power quality disturbances such as the voltage rise, overloading of the gird and harmonic distortion due to the grid-tied distributed photovoltaic system were discussed. Distortion in Current waveform is much more serious than voltage waveform. The dominant causes for high total harmonic distortion (THD) are identified as low load operation of inverter, which rises from low solar radiation.

3.3 Faults and System Protection

In conventional radial power delivery systems power flow in only one direction, addition of renewable changes energy flows which now can flow in either direction, therefore the role of protection system has become crucial in the operation of the grid. The following protection issues must be considered when renewable is to be integrated with the utility: reverse power flow, Fault current capacity, anti-Islanding, reduced reach of distance relays, voltage profile, Ferro-resonance oscillations, power quality (harmonics, transient etc.), inadvertent tripping, auto re-closing, selectivity and grounding. The protection devices should have synchronized control in order to address these issues. Major component of solar PV system is the inverter which interface the solar PV system with grid and converts the direct-current (DC) power produced by the PV array into alternating-current (AC) power that matches utility power requirements. The power flows is bidirectional between inverters and grid, any occurrence of large power quality disturbance forces the protection system to disconnect the PV array or to shut down the inverters as it cannot handle such perturbations [1]. Faults in PV arrays affect the performance and reliability of the entire system. Line-line and ground faults in PV arrays cause fire hazard, damage the PV module, connecting cables and large amount of energy loss [55], [59]. Usually to protect the PV array HRC fuses or circuit breakers are employed. These devices provide the protection only if the fault current magnitude is high [54-55, 58, 70, 76]. In PV modules ground fault develops because of the solar cell short circuiting to grounded module frames or insulation failure of cables. Ground fault generates a DC arc, which may become a fire hazard. Line to line fault occurs due to incidental short circuit between current carrying conductors or insulation failure of cables [60-61]. Modern inverter design has extensively improved protection scheme. Protective relaying function has been incorporated in their control circuitry, any deviation outside the limits of voltage and frequency will cause the inverter to shut down and disconnect from the utility line within a few cycles. Anti-islanding protection is also implemented in present grid-connected inverters, it prevents the inverter from continuing to work when the grid is not energized [62-63]. But the major problem with inverter is their extremely low fault current capacity. This affects the sensitivity and operation of the over current relays in the system [1]. Paper [64-66] presents the sensitivity of the PV inverter due to power quality disturbance, malfunctioning of protection devices and spurious tripping of the inverters due to such events which has the negative impact on the performance of system. A severe power quality problem like harmonic resonance can also trip protection devices and cause damage to sensitive equipment [50, 67]. Bower et al. [68] reported, PV systems connected to other sources of energy such as batteries, inverters, standby generators, and the utility grid , causes occurrence of unexpected ground faults due to flow of leakage current through stray inductance, capacitance and resistance which requires a proper ground fault protection scheme. Park et al. [69] presented an optimal solution for the mal-function problem using the symmetrical components of fault analysis.Phuttapatimok et al. [71] addressed the fault contribution of a grid-connected PV system in the event of an unplanned islanding and unavoidable effects on the protective devices. In [72] a case study of Kinmen power system was done to investigate the steady-state and transient characteristics for the high penetration PV systems due to the various disturbances, such as change of solar irradiance, tripping of PV generation and three-phase short circuit. The reach of an impedance relay gets affected, due to mismatch in impedance between downstream and upstream locations. There is also possibility that due to high impedance fault the over current protection may not operate in sufficient time [73-75]. References [77-78] address the issues like Fault Ride-Through and Low Voltage Ride-Through capability of the system, effect on voltage stability due to occurrence of fault in a large grid connected PV system and simultaneous protection and control challenges. Due to rapid growth in solar PV integration to grid, potential frequency stability problem was observed in Germany [79]. The increase in frequency above thresholds required immediate disconnection of PVs. Boemer et al. [79] addressed the related potential frequency stability problem and analyzed the mitigation measures.

3.4 Miscellaneous Issues

References [80-81] analyzed the existence of strong electromagnetic interference current at radio frequencies on the AC and DC lines due to the high frequency switching of inverters and standardized the electromagnetic compatibility level of solar PV system. Araneo et al. [82] presented the radio frequency behavior of grid connected PV plants and the places which provide the path for the flow of electromagnetic magnetic interference current. Specific guidelines are proposed to get the reliable operation of the plant form an EMC point of view. Output power in PV system depends on the inverter and it operates on unity power factor. PV system supplies the real power to the system and does not consume any reactive power [83]. In [84] non-unity PF advanced inverter functions were identified since non-unity PF decreases conversion efficiency therefore their effects on the performance of the inverter and the ability for hardware to meet the programmed real and reactive power levels were assessed.

4. CONCLUSIONS

Solar PV systems are expected to play a promising role in meeting future electricity demand. The integration of solar PV provides various advantages but the existing grid system like in India is not compatible enough to accommodate large number of such systems in power system network. Moreover technological changes such as information communication technology along with advanced instrumentation and control is also required to make the existing system responsive. Various issues and challenges have to be addressed in order to move towards the smart grid era.

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