

Perspectives On Impact of High Penetration of Renewable Sources on LV Networks

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Abstract—In most countries, electricity power grids have not undergone extensive modernization and/or liberalization. They are still predominantly vertically integrated i.e. designed and operated top (Generation)-down (Distribution / Loads). Increasing electricity demand and rising costs are causing congestion and strain on power distribution networks operations. Fossil fuels are in decline and blamed for most negative environmental and climatic impacts on world economics and societal maleficence. Throughout the world they are heightened impetuses to migrate to cleaner Renewable Energy (RE) sources and incorporate more intelligence in the utilization of energy. This has birthed the concept of smart grids with high participation of various clean energy sources. Hybrid renewable energy generation (HRE) systems are complementary technologies that have potential to mitigate climatic variability effects which are still a challenge with respect to dispatchability of RE resources. The emerging smart power grids are no longer unidirectional in terms of energy flow, but also allow users to inject energy back into the grids. The bi-directional flow of energy has a significant positive impact on overall systems design and operation. This article provides an overview of the preliminary work that done to assess impact scenarios on power grids with increased penetration of RE. Simulation results show possible negative factors that may affect QoS parameters of typical LV power networks.

Keywords—Hybrid systems, grid integration, wind energy, solar-PV.

I. INTRODUCTION

Traditionally power in electricity grids flows from large power stations to passive end users. Currently the power grids are expected to meet several technical requirements such as improved reliability, scalability and security [1][2]. A microgrid is a group of distributed generating (DG) sources and loads normally connected to the main grid at distribution level or on off-grid feeders or operating alone Fig. 1. The latter operational mode is described as islanded. This paradigm shift is altering the traditional landscape of electricity generation, transmission, and distribution by providing two-way flow of electrical energy [3][4] and integration with RE resources at the distribution level. The new imaging microgrids are relatively small and can be situated close to the loads they supply to increase the reliability and reduce transmission losses. However due to the anticipated growth in sheer numbers of these microgrids at distribution level, they will increase both operational and design complexity of the current power systems [5]. The primary RE sources are solar photovoltaic (PV), wind turbine (WTG), battery energy storage systems (BESS), fuel cells

and micro hydro turbines. Combing these technologies into one system results in hybrid microgrids.

This rest of the paper is organized as follows; Section II outlines a common physical layout and basic circuit for small signal modelling. Sections III looks at current challenges and opportunities for microgrids control. In the subsequent sections IV–VI basic models for PV, wind turbine and fuel cells are outlined. Simulation results of uncontrolled 100kW PV plant subjected to variable climatic conditions are presented in section VII. The paper concludes in section VII and VIII by identifying possible impact scenarios that require further investigation depending on the specific geography and topology of a system as presently they are no universal microgrid models [6][7].

II. MICROGRID CONFIGURATIONS

Microgrids can be configured in radial, chain, ring or mixed connections, [8][9]. A radial illustration is given in Fig. 1 where multiple microgrids [10] connect to a point of common coupling(PCC). Dual modes of operation are possible, viz. grid-tied and islanded mode. Islanded microgrids are ordinarily not connected to the utility system and they operate independently as electrically isolated islands for long time periods. Their control is more complex as the inertial smoothing effect of the infinity grid network is absent. Islanded operation may be attractive for high power supply reliability specially for facilities such as base stations, hospitals, data centers etc. Another attraction of microgrids is that in islanded mode,

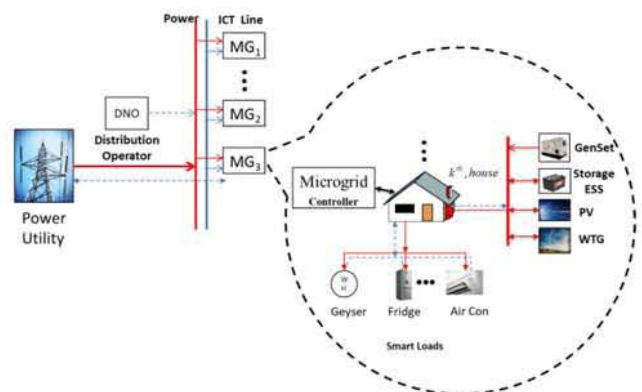


Fig. 1. Typical Microgrid layout

can still feed loads within the island despite possible upstream faults in a main grid. Microgrids require power electronics interfaces and sophisticated coordination among themselves as well as among different customers or areas. Small signal control models have been developed [12] to study islanding transients but computational time is still an issue during simulation when the DG network is large.

The analysis strategy commonly applied is appropriately time scaled average phasor dynamics models [12] [14], small signal linearization, order reduction via perturbation methods etc. Power flow equations are constructed from circuit simplification as depicted in Fig.2 subject to various assumptions on parameters and operational state of the RE sources [13].

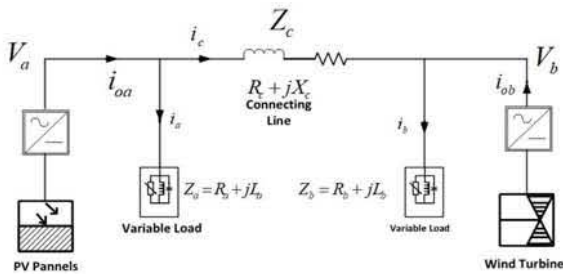


Fig. 2. Microgrid Model

Despite the challenges, microgrids have the potential to bring new flexibility in terms of load balancing, dynamic frequency control as well voltage support to the distribution system and thus will continue to receive much interest and grow. Various configurations are being investigated [15] including vehicle-to-grid (V2G) and Grid-to-Vehicle (G2V) topologies where motor vehicles battery storage/discharge are employed to support grids capacity and general voltage / frequency stability of the systems.

III. CHALLENGES & OPPORTUNITIES IN DISRUBUTED GENERATION

The broad problems in the operation of microgrids in the context of distributed generation have been outlined in surveys [1][10][16]. About five categories of research undertaken in the literature are identifiable i.e., (i) islanding to grid tied or vice versa operation control with focus on voltage and frequency transients induced by the changeover or switch mode change over, (ii) control in autonomous mode, (iii) stability and reliability of microgrids, (iv) power quality issues, and (v) operational optimization or scheduling against a background of ‘uncontrollable primary’ sources as well as competing operational and capex costs for various RE elements.

Owing to the stochastic behaviour of both solar and wind, one of the major hurdles in the design of PV and wind systems is securing continuity of supply power. Solar incidence is predictable, but cloud cover is not. The consequence of stochasticity of the RE sources is that for a given microgrid system a mixture of dispatchable and non-dispatchable, inertial (slow dynamics) or non-inertial (fast dynamics) technologies is used giving rise to the hybrid renewable systems. The operating characteristics of the individual constituent sources are different [12]. In this regard, work has been done to investigate the stability of power systems with the integration of storage elements employing fuel cells and micro turbines, large scale wind turbines and solar panels

[17]. Major research efforts are currently directed at energy management and the role of demand side management techniques [10]. For such hybrid systems the daily outputs are more stable, as the energy sources mutually compliment to offset the diurnal variations in output. Variations emanating from seasonal changes are also offset. Hybridization also implies installations will require smaller storage capacities.

DG sources connect to microgrids through electronic converters acting as voltage sources. These converters are paralleled, see Fig.1 and 2. The output voltage of distributed energy resources can be DC or AC with variable frequency. Intermediate converters are used for linking to the main grids [12]. Voltage sourced converters, coupled with isolating transformers are commonly used. In practice we find DG sources are spread over relatively large geographical areas. Under such conditions circulating currents among the converters can appear due to effective output impedance mismatch. Various techniques of droop control methods [13] have appeared in the literature making it possible to avoid communication overheads between converters. However, droop control strategies suffer from load-dependent frequency and amplitude deviations in part due to assumptions on X_c/R_c ratio [16] of Fig. 2. Parameters R_c and X_c relate to the connecting link. The concept of virtual impedance has been widely applied to recover $X_c \gg R_c$ assumption.

DG systems can disrupt the coordination operation of system protection due to feed-in currents. In typical top-down traditional approach protection settings are set based on fault current levels and parameters of the distribution network within a given locality. The design and parameter settings follow a ‘fixed’ approach. This means settings for protection equipment remain unchanged for as long as the top-down networks stay fixed. DG units can reduce the driving point impedances at the PCC thus effectively increase currents at a fault and reduce it at the protection device for the period prior to the time the DG pick up the fault and disconnects. Fault detection becomes harder and the coordination among protection devices becomes difficult. In addition, fault currents at points of system protection will have extra dependency on which DG units are connected and operating at a given instant. Changing fault currents with the introduction of DG can thus lead to failure of co-ordination with the result that faults propagate beyond the first level of protection. Safety and reliability are reduced in such instances.

In contrast to the passive traditional operational approaches, new methodologies coupled with the ever-expanding role of power electronics are poised to enable active management of distribution systems such as using DG systems as loads for voltage and fault current level control. Our work focuses on stability, control and scheduling of microgrids as penetration of distributed energy sources in the grids increase.

IV. PHOTOVOLTAIC SOLAR CELL MODEL & BOOST DC-DC CONVETER

In photovoltaic power systems, both the photovoltaic modules and boost DC-DC converters are nonlinear and time-variant. Models of array systems can be developed based on the expressions given in (1)-(4). The PV operate in MPPT mode. Individual PV cells are grouped in larger

units to make PV modules. The modules are then interconnected in a series-parallel combination to form PV arrays with higher voltage or current or both capacities. PV cell voltage is a function of the photocurrent that depends on the solar irradiation level. The current output of the PV cell is represented by (1). For a PV array made-up of N_s series and N_p parallel modules, the voltage and current output are given by (3) and (4). Power output is the product of its current and voltage as formulated by the standard expression in (5).

$$i(t) = I_{ph} - I_o = I_{ph} - I_{sat} (g_{pv} - 1) \quad (1)$$

where,

$$g_{pv} = e^{-\frac{q}{AKT_c}(v+iR_s)} \quad (2)$$

$$V_{pv} = N_s [V_{ref} - \beta(T - T_{ref}) - R_s(T - T_{ref})] \quad (3)$$

$$I_{pv} = N_p [I_{ref} + 0.001\alpha G(T - T_{ref}) + (0.001G - 1)I_{sc}] \quad (4)$$

In (1) I_{ph} is the light generated current in the PV cell and I_o is the reverse saturation current of equivalent diode model. T_c in Kelvins is cell temperature and A is ideality factor. K is Boltzmann constant, q is electron charge and α is current temperature coefficient. G is irradiance, R_s is series resistor, I_{sat} diode saturation current, β is voltage temperature coefficient and v is photovoltaic voltage. V_{ref} is the output voltage, N_s is number of series connected modules and N_p is number of parallel connected modules.

$$P_{pv} = I_{pv} V_{pv} \quad (5)$$

In [2] is discussed the piecewise linear model of the PV dynamic resistance, r_{pv} defined as;

$$r_{pv} = \frac{dv(t,i)}{di} \quad (6)$$

For constant irradiance and temperature I_{sat} and I_{ph} are constant, it can be shown that $r_{pv} \approx -k\nu(T) + r_{pv,o}$ for some constant k . Through this definition the operating regimes of PV cells can be piecewise linearized into 'current source region' and 'voltage source region' with two intermediate power regions. The dynamic conductance is low in the constant current region and high in the constant voltage region. Through appropriate PWM feedback control of boost converter the frequency dynamics of the converter are fairly flat from dc up to about 1 kHz in both the constant voltage source, constant current source and power regions of the linear approximations [3]. This implies a fairly constant voltage source V_a in Fig.2 is a good approximation.

V. WIND CONSTRAINTS, TURBINE MODELING

The power that can be extracted from the wind is very dependent on the wind speed ν due to the cubic law (7). In (7) the parameter ρ is the air density, A is the area swept by the blades and C_p is a variable power coefficient of the wind turbine.

$$P_w = 0.5\rho AC_p \nu^3 \quad (7)$$

Strong winds result in above rated energy yields hence the need for curtailment controls to avoid possible mechanical structural damage. On the other extreme, low wind speeds may not be enough to meet the demand or start-up the WTG. Such swings reflect in unstable frequency and voltages from the turbines at point of common coupling with the grid. This calls for control and regulation in order to match the frequency and voltage on the grid. Major model components of WTG are the aerodynamic power transfer phenomena, the mechanical drive trains, tower structures stiffness dynamics, the generator and the pitch angle control subsystem [18].

They are three aspects to turbine operation models; transfer of wind energy to the turbine's blades, transfer of wind turbine energy through the coupling drive mechanism and finally the electro-mechanical energy conversion. Various types of generators can be mounted on the wind turbine. The double feed induction generator (DFIG) have gained pre-eminence on account of converter savings and efficiency. The aerodynamic torque, T_a driving the wind turbines, generates the useful power. A thrust reaction force (9) is exerted normal to the wind turbines plane of rotation. This force causes bending and oscillatory mechanical stress of the blades and the WTG tower structures.

$$T_a = \frac{\pi\rho R^2}{2} \cdot \frac{1}{\omega_r} \nu^3 \cdot C_p(\beta, \lambda) \quad (8)$$

$$F_f = \frac{\pi\rho R^2}{2} \cdot \nu^3 \cdot C_p(\beta, \lambda) \quad (9)$$

ω_r is rotor speed, R the rotor radius, ν_r the effective rotor speed, and C_t is the thrust coefficient. Both C_t and C_p coefficients have a non-linear dependence on the rotor pitch angle β and the rotor tip speed ratio λ . This implies these two parameters will vary for a specific make of wind turbine. The thrust reaction force F_f causes the tower and nacelle axial movement 'z' resulting in effective wind speed (9) of;

$$\nu_r = \nu - z \quad (9.a)$$

$$\lambda = \frac{\omega_r R}{\nu_r} \quad (9.b)$$

A. WTG Drive Train Model

For the turbine rotor assemblies, gearboxes and electrical generators' components the three-mass linearized model characterised by respective inertias, viscous friction and stiffness spring constants can be used. The coupling between the turbine and gear box is characterised by a spring with torsional deflection angle θ . A complete third order approximate model take the form,

$$\begin{bmatrix} \dot{\omega}_r \\ \dot{\omega}_g \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ 1 & \alpha_{31} & 0 \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_g \\ \theta \end{bmatrix} + \begin{bmatrix} -\eta_1 & 0 & 0 \\ 0 & \eta_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_a \\ T_g \\ \theta \end{bmatrix} \quad (10)$$

$$\underline{y} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_g \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} T_a \\ T_g \\ \theta \end{bmatrix}$$

The various parameters, α_{ij} [19] are machine dependent. Specific generator electrical power output model will depend on the machine type and grid to which it is connected. A simplistic model for the generator output is given in (11).

$$P_e = T_g \omega_g \quad (11)$$

The generator electromechanical torque T_g is derived in the next section when using a permanent magnet squirrel cage induction generator (PMSG).

B. Torque Equation: Permannet Magnet Synchronous Generator.

Dynamic modeling of PMSG can be described in direct/quadrature (dq) reference system [1].

$$v_q = -\left(R_r + \frac{dL_q}{dt}\right)i_q - \omega_e L_d i_d + \omega_e \lambda_m \quad (12.a)$$

$$v_d = -\left(R_r + \frac{dL_d}{dt}\right)i_d + \omega_e L_q i_q \quad (12.b)$$

Where R_r is the stator winding resistance; L_d and L_q are stator inductances in d and q -axis respectively; i_d and i_q are the currents in direct and quadrature axis, respectively. The electrical angular speed of the generator is defined by ω_e ; λ_m is the amplitude of the flux linkages established by the permanent magnet viewed by the stator windings. The expression for the electromagnetic torque is defined in(13).s

$$T_g = p \left(\frac{3}{2} \right) [(L_d - L_q) i_q i_d - \lambda_m i_q] \quad (13)$$

Where p is the number of pole pairs of the machine. The relation between electrical angular speed ω_e and mechanical angular speed ω_m is given in (14);

$$\omega_e = p \omega_m \quad (14)$$

VI. WIND , SOLAR SIMULATION, HYBRID CHALLENGES

Based on the above simplified model equations a 100kW solar farm was configured in MATLAB's Simulink toolbox. The solar irradiance and temperature inputs were configured in Simulink following Fig. 3 The grid source was set at 100kVA through a 20km transmission link. The PV solar farm with MPPT tracking connected to the grid via a three-phase average voltage source converter model. Three, 3 phase radial loads are tapped from the 20km link. Fig. 4 shows response of the system when solar irradiance and operating temperature vary. Of note is the variation of power output and line voltage in response to the induced climatic factors.

VII. IMPACT SCINARIO ANALYSIS

Hybrid PV and wind power plants have inherent nonlinearities, certainties as well as changing dynamics. QoS concerns encompass voltage distortion, swell, sag, transients' harmonics, voltage imbalance etc. Consequently, smart grids require advanced control methodologies to resolve these phenomenon effectively. Use and adaptation of efficient control methods not only will it increase the performance of these systems but could increase the availability hours of solar and wind plants. This can potentially reduce unit cost of kilowatt-hour (kWh) produced.

Wind and solar energy sources both have high intermittency Fig. 3. Wind speed and direction changes continually and seasonally. Sunlight is only available during daylight hours which is variant according to the geographic location of a station. From the point of view of a grid both wind and solar energy can be viewed as aggregate resources, with outputs that vary within ten to sixty minutes time intervals. In this way they do not represent the same form of outage transients as unplanned interruption of large base load generators.

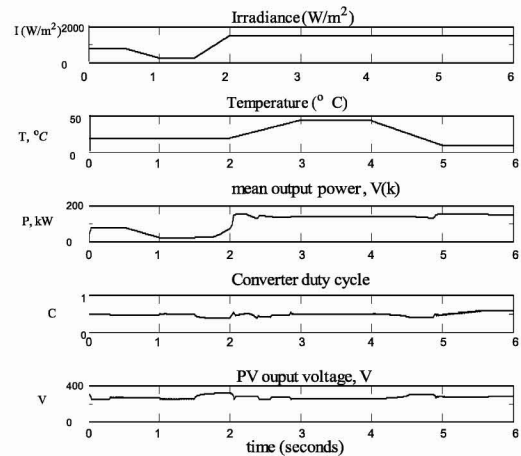


Fig. 3. PV average model showing variable irradiance and temperature power output

Distributed generators can support weak electric grids, aiding grid voltage and improving power quality. In certain circumstances, distributed generation can be used in conjunction with high energy density thin film capacitor banks for management of power flows as well as active and reactive power balance in the networks.

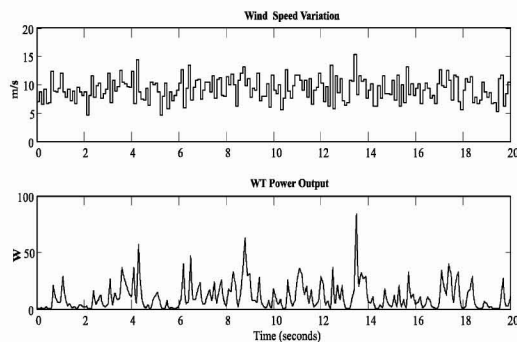


Fig. 4. Wind speed and power variation

VIII. DISCUSSION AND CONCLUSION

The work that has been carried out demonstrates that if the RE sources are not properly coordinated to the grid, with increased penetration of renewable energy, low frequency swings of voltage and frequency will begin to grow in the grid. It is critical that these phenomena are clearly identified in any specific microgrid topology to avoid propagation of faults which can potentially lead to wider system shutdown or failures. More specific representative configurations will be built for simulation and further studies based on models presented here. Storage has a stabilizing effect on the performance of microgrids.

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