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Power system studies considerations for Microgrid design

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Abstract—The value-proposition for Microgrids depends largely on the need and application. A Microgrid can be described as a group of interconnected loads and distributed energy resources (DER) inside some distinct electrical boundaries that act as a single controllable unit relating to the grid. It should be capable of safe transitioning from the grid and reconnection back to the grid; with the voltages, frequency, etc. of all devices still operating within their allowed limits. Although system resilience and continuous supply is one of the main proponents for the establishment of microgrids, it could also be used to electrify an off grid or remote area, far from the grid. The mode of operation as well as generation types and sources, together with the current protection devices and schemes, will determine the extent of power system studies that will be conducted when planning and designing a Microgrid. This paper highlights the typical power system studies that needs to be considered, when designing aa Microgrid.

***Index Terms*— Microgrid, Distributed Energy Resources (DER), power system studies, unplanned islanded mode.**

I. Background and Introduction

The transformation of a part of the electric network which has generation and loads, has been referred to as Microgrid by some utilities. Such loads maybe controllable and can be synchronized while grid connected or operating as an island. The generation can be Distributed Energy Resources (DERs), (such as storage devices, solar PV, or controllable loads) [1].

This paper highlights the grid impact studies associated with Microgrid designs as well as a step by step guide on conducting the detailed engineering studies for Microgrids. The power system studies described in this paper may not be directly applicable to remote Microgrids.

This paper has been structured as follows: General Microgrid types and operational modes are described in Section II. The hierarchy considered before a Microgrid is designed is highlighted in Section III. Section IV explains the details of the applicable power system studies considered for Microgrid engineering design analysis. Section V describes a North American utility case study; while. Section VI illustrates the key observations and conclusion.

II. An Overview of Microgrids

A. Types of Microgrids

Often times, power generation sources for Microgrids can be misconstrued as comprising only of renewable energy sources, unfailing power sources in outages have historically been from other fuel sources such as diesel or gas power [2]. According to [3-5], five main Microgrids types are:

- Commercial or Industrial Microgrids: While the goal is to bring down normal cost of operation as well as demand, some core loads, like data centers are prioritized during outages.
- Community or Utility Microgrids: The goal is enhancing reliability and boosting community participation.
- Campus/Institutional Microgrids: Some campuses potentially use excess generation within their Microgrids as remunerated power exports to the grid.
- Military Microgrids: Settled bases and the likes use Microgrids for digital and physical safety.
- Remote Microgrids: These are for areas far away from the grid, often operated as islands.

B. Microgrid operational modes

Microgrids can operate in several modes. These are [6]:

Grid-connected mode: The connection of the Microgrid to the existing utility system allows for power interactions to and from the utility grid and vice versa.

Island transitioning mode: This is a planned or an unplanned disconnection of the Microgrid from the main utility grid.

Island mode: This is a scenario in which a Microgrid can self-generate and supply all its loads without compromising any power quality and system reliability requirement. The Microgrid has autonomous operation from the main utility grid. There are local controllers which creates and provides safe, reliable, resilient and continuous operation, such that demand and supply is balanced within the Microgrid and system reconfiguration can be done seamlessly.

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III. Hierarchy of System Analysis

A. Feasibility analysis

The economic viability and value stream of the Microgrid is typically determined via feasibility assessment/analysis. The key questions that are often answered during feasibility assessment includes:

- What is the best cost effective method to power the proposed Microgrid while keeping it resilient?
- What typical configurations as well as equipment are required for the proposed Microgrid?
- What is the duty cycle of the generation assets? What types of generation assets will be utilized?

The objective of this study is to identify and size the proposed Microgrid generators, such as DER, and elements of load management, which can be load shifting and load curtailment. The Microgrid system sizing is then used as a basis for subsequent power system analysis of the Microgrid. The feasibility study typically utilizes a combination of two modeling tools – the Distributed Energy Resource Customer Adoption Model (DER-CAM) and the System Advisor Model (SAM).

DER-CAM, was developed by Lawrence Berkeley National Lab [7], is a techno-economic tool that can be used to simulate DER adoption for buildings and Microgrids. It determines the lowest cost combination and dispatch of DERs and electricity purchases (if grid-tied) to supply loads within a Microgrid. DER-CAM works by optimizing DER adoption and hourly dispatch over the first year of operation by translating the problem as a mixed integer linear program in the General Algebra Modeling System (GAMS) and minimizing the combination of system costs and/or emissions. Key inputs to the model include end-use load profiles, available DER technologies, site-specific parameters such as location constraints and space constraints, and local energy and fuel costs. The System Advisor Model (SAM), developed by the National Renewable Energy Laboratory [8], is a DER performance modeling tool that can be used to model assets such as solar PV, wind and energy storage. SAM makes lifetime performance predictions for grid-connected power projects based on a set of specified system design parameters (e.g. module model, inverter model, configuration) and inputs such as weather information.

Several sensitivities can be checked during the feasibility analysis, some of which can include [9]:

- Islanding Duration – This looks at the period in which the Microgrid will be autonomously operated. It is often measured in hours.
- Additional DER Investment – A baseline DER e.g. distributed solar PV is used in all scenarios. This parameter identifies what new DER will be included within the Microgrid.
- Load Shifting – During Microgrid islanded scenarios, there could be a need to have some controllable loads deferred. This parameter identifies and monitors the percentage of shifted load during the day; which can only occur in a single day. It does not occur over several days.

There can be other load sensitives depending on the Microgrid needs and application.
Once the feasibility analysis is completed and the Microgrid is found viable; a detailed engineering design analysis can commence.

B. Detailed engineering design analysis

The detailed engineering design analysis entails modeling and analysis that is utilized to get a better understanding of how to evaluate the performance of the overall Microgrid system and DER assets in grid tied and islanded mode. These detailed studies are also referred to as interconnection studies. Interconnection studies allows the Microgrid designers to assess system resilience, reliability and safe operation of various Microgrid operational modes. The grid impact studies, which may include load flow analyses, short circuit analyses, power quality studies, grounding, protection coordination, stability, including motor starting and black start studies; should be done to have a thorough understanding of the Microgrid system's planning and operational needs.

C. Models for interconnection studies

The models that may be required for various Microgrid interconnection studies vary. In addition, it depends on the type of Microgrids, the operational mode as well as the application of the Microgrid.

In general, the static and dynamic load models are required. In addition, all the generators along with their controllers must be included in the model. If the Microgrid is carved out from an existing utility system/network, all the transformers, generators (along with their controllers), circuit models and detailed data of every component and element of the existing utility system/network must be included in the overall analysis.

A Distributed Energy Resources Management system is required through the development of integrated control and management systems for Microgrids. A Master Microgrid Controller (MMC) eases the roll out of the DERMS within a Microgrid [3]. In as much as cyber security cannot be considered as a system study, the details of a potential cyber-attack on the Microgrid need to be examined, analyzed and prioritized. Often times, this analysis is over-layed and embedded with the protection and control; along with the MMC and Distributed Energy System management (DERMS) configured for the Microgrid [3]. Some vendors have termed such controllers "Cybersecure Microgrid Controller" [10].

The benefits of co-simulation cannot be over-emphasized most especially, when working with intelligent power systems. More precisely, the joint effect of coupling any ICT infrastructure with an intelligent power system framework can be studied and analyzed using a real-time co-simulation platform [11]. In some instances, co-simulation analysis is considered to check the effectiveness and impact of combining the controllers of all these systems; along with their functionalities. The co-simulation aspects of Microgrids is not the focus of this paper.

IV. APPLICABLE POWER SYSTEM STUDIES

All the information mentioned in the previous section will be needed for quasi-static time series simulations that will be performed over successive time intervals; typically, over a day or a year with consideration to load and generator variations. In addition, time domain simulations will be required to have a good understanding of the responses of the Microgrid controllers to various Microgrid events and Microgrid scenarios.

A. Load flow studies

The study aims to ensure that the Microgrid has adequate equipment rating, and to demonstrate that there are no voltage or thermal overload conditions during all operating modes of the Microgrid. This is also conducted to check if the Microgrid generation is enough to support the islanded load. Steady-state thermal, voltage, and frequency analyses using any power flow program is needed to be performed, for quasi time series simulation of the load conditions in the Microgrid.

B. Short Circuit analysis

In general, a Microgrid must be able to provide adequate protection in all Microgrid operational modes; but, the challenges differ in these grid-connected and islanded operating modes. Short circuit analysis should be performed for various Microgrid configurations and should include a review of inverter capabilities of DER, the impact of overall system protection and suitability of existing circuit breakers, other fault current interrupting devices, and related equipment. Others include the impact on the operation of network protectors; if a networked Microgrid is considered [9, 12]. Furthermore, the impact of magnetizing currents from transformers during the transitions should be examined.

C. Protection Studies and Analyses

The need and requirements for any extra protection equipment and infrastructure can only be established after observing the effect and capability of the existing protection [9, 12, 13]. A suitable protection operating philosophy and protection schemes that can be designed and recommended for any Microgrid will only be effective if the suitability of the current protection is checked for all Microgrid operation scenarios. If it is found out that the existing protection philosophy and schemes is not satisfactory for all Microgrid operation modes, a new protection scheme becomes inevitable. The factors to be considered for designing the new protection schemes includes the selected protection philosophy, location of the protection devices and the effectiveness of the protection devices, such as relays, breakers, etc. It is also important to know and understand the capabilities of the inverter-based generation within the Microgrid; before starting the protection coordination studies. With the inverter-based generation proficiencies known, the consequences of the generation source(s) short circuit implications on all relevant Microgrid scenarios can be analyzed.

D. Dynamic Analysis

Dynamic stability and response analysis may be required to be performed for peak loads and off-peak loading conditions to know the effect of the Microgrid during islanded and grid connected mode. These studies could be needed to demonstrate voltage control, load-frequency control, load-rejection during the grid synchronization and islanding states. A black start study is often required to demonstrate the resiliency and suitability of the Microgrid during a complete Microgrid system shut down. In addition, the impact of inrush current during transformer energization will be required. Obviously, if a Microgrid master controller (MMC) will be included within the Microgrid, the interaction between the MMC and all the controllers within the Microgrid need to be analyzed.

V. CASE STUDY

The detailed engineering design in the use case was conducted using DIgSILENT PowerFactory [14]. The studied grid is a distribution grid within the service territory of a distribution utility in the United States. The utility decided to implement a Microgrid on the feeder as a proof of concept. Due to the sensitivity of the location of the proposed Microgrid, the feeder information, synchronous generator and inverter models and sizes are not described in this paper. All the loads in the base circuit model came as a constant power load from the utility. The power system analysis was illustrated using two different DER generation types connected to the test distribution grid. The test grid was selected because it represented a typical distribution grid in North America.

The synchronous generator is a diesel generator; equipped with both a governor and an excitation system to regulate both the island voltage and frequency. A step response test was initially conducted (see Figure 1) and the governor models were tested as well.

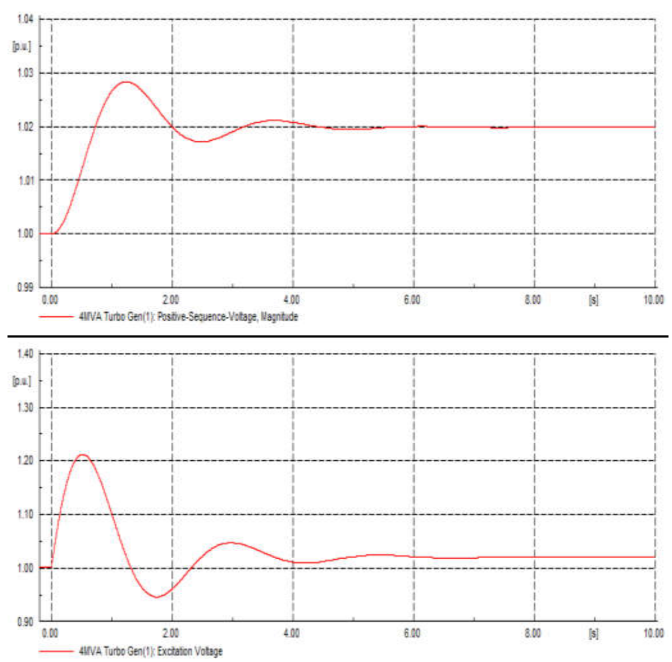

Figure 1: Step response of the synchronous generator excitation system

After effectively modelling the synchronous generator, an inverter-based distributed energy resource was included in the Microgrid. The rotating generator was used as the isochronous generator. The control implemented on both the diesel generator and the inverter is a master-slave topology where the synchronous generator adopts both the grid frequency and voltage droop; whereas the grid following current source inverter was used as a slave. The inverter was specifically designed to comply with the requirements of IEEE 1547:2018 as well having the capability of detecting unintentional islanding scenarios [15, 16].

Microgrid controller utilized in this use case was layered as an additional control, with the aim of assisting with system dispatch, such as generator start/stop; triggers Microgrid feeder adaptive protection coordination, responsible for power balancing between generators and consumers, ensuring the necessary data logging and acquisition for the DERMS and Cyber security interface. In addition, the controller combination was also used as the main control capable of operating and switching between grid connected mode and islanded modes and the under frequency load shedding functionality was also included in the controller model.

The results presented in this case study is for an unplanned island. The grid breaker opened at 0.3 secs and Figure 2 shows the active and reactive power measurements on the point of coupling metering current transformer. The graphs in Figure 2 indicates that prior to 0.3 secs, there was active and reactive power exchange between the main utility grid and the Microgrid. At about 0.3 secs, the Microgrid was completely islanded. Here, the values of both the grid active and reactive power after the 0.3 secs were 0 kW and 0 kVar respectively.

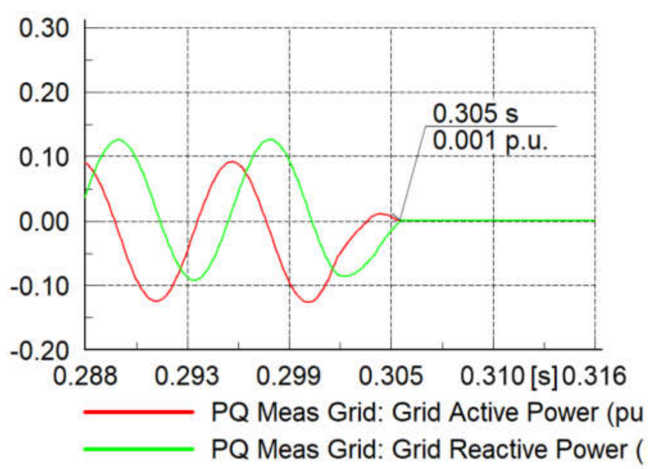

Figure 2: Power flow indicating unplanned Microgrid island transitioning state

Prior to the island formation, it should be noted that both the rotating generator and the inverter-based generation were online. Hence, immediately after the island was created, the synchronous generator became the reference machine and was defaulted to operate in voltage droop control. After the island was created, there was a slight decrease in island frequency as shown in Figure 3.

On the other hand, voltage and frequency of the inverter remained almost constant after the unplanned island was created as shown in Figure 4. This was due to responses of the faster controllers incorporated within the inverter. The voltage and frequency of the inverter operated with the recommended limits, as suggested in [16].

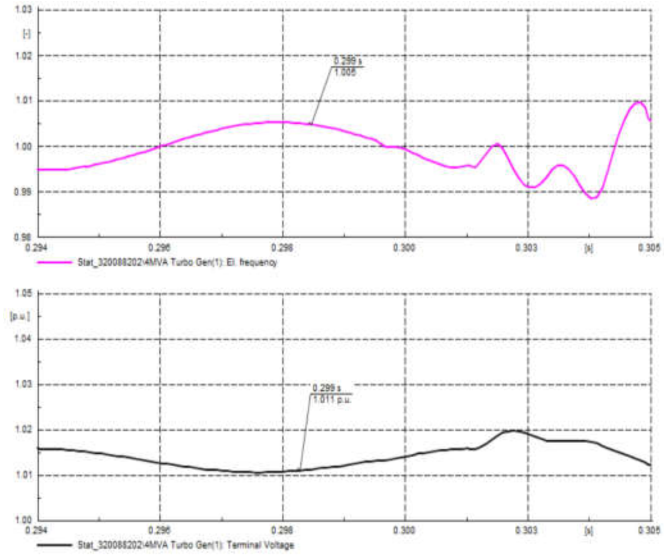

Figure 3: Rotating generator frequency and voltage responses in Microgrid

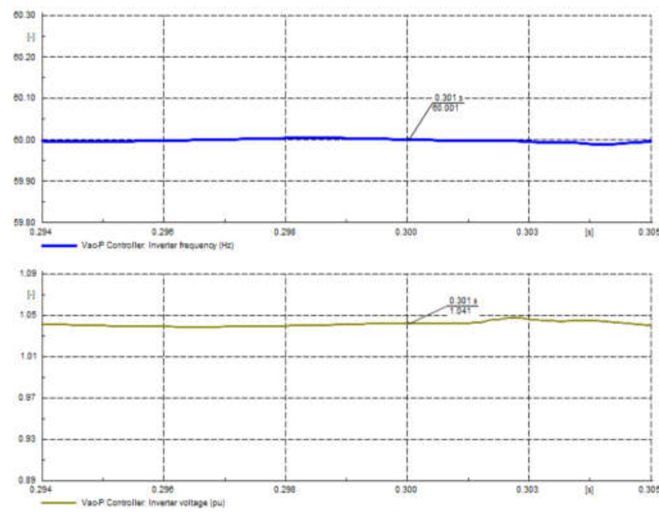

Figure 4: Inverter- generation frequency and voltage responses in Microgrid

These results implied that the synchronous generator determines the Microgrid primary frequency and voltages; whereas the inverter is only obliged to inject active and reactive power; thereby following the set frequency and voltage by the rotating generator.

After the unplanned island creation was tested and there were no noticeable perturbations in the voltages and frequencies of the generators and all the loads were adequately supplied, the reliability and resiliency of the Microgrid was tested. This was done by simulating several scenarios within the islanded Microgrid. The scenarios simulated are explained below:

- Compared the load step and fault clearing capabilities (with a very short fault duration) of the ALL generators within the Microgrid. Then, the following faults/ disturbances were considered within the islanded Microgrid:

- o Step changes of the load in the Microgrid. i.e. Load loss at 25%, 50%, 75% and 100%
- o Variations of various combinations of the production and dispatch of all the dispersed generators (both rotating and inverter-based) at 25%, 50%, 75% and 100%.
- o Fault on the forming synchronous generator and the response of the inverter-based DER
- o Checked the impact of varying external grid inertia and maximum frequency deviation in the Microgrid stability during both transitioning period, i.e. island formation and grid reconnection.

- In addition, the dynamic responses of the Microgrid controllers to grid events such as loss of a large three phase load, load step and fault clearing capabilities of the synchronous generator in the islanded Microgrid were verified.
- Black starting capability of the Microgrid was tested to observe the impact of cold-load pickup and inrush current requirement of the motor-based loads. For the black start study, the main generator was brought to its spinning state (normal operation at no load) using a small diesel generator before connecting the generator to the de-energized bus. The effectiveness of the Microgrid controller was also demonstrated by using a startup generator that wouldn't be able to handle the load requirement. However, the Microgrid controller was able to control some sensitive loads to be brought online in steps so that the generator can support the load.
- For the motors' starting, various three phase induction motor sizes were simulated during the black starting. For the smaller motor sizes, motor starting was successful when the Microgrid can supply the required inrush current required to start the motor without severe voltage drop at the motor terminals. However, as the motor sizes was gradually increased, the motor failed to start when the electrical torque produced was less than the torque required to start the motor.
- The final step was the modelling of all protection devices such as CTs, relays, etc. within the Microgrid and then checking the existing feeder overcurrent protection against bi-direction current flow, nuisance tripping, etc. With the existing protection coordination checked, there was a need to re-coordinate all the protection devices with various settings using adaptive protection that is compatible with various operating modes of the Microgrid. The details of the protection coordination, suggested solutions to the protection challenges as well as the new recommended settings are not included in this paper.

VI. Key Observations and Conclusions

The simulations of different Microgrid operation scenarios indicated that the applied generators' control schemes, as well as the interactions between all the controllers within the Microgrid, the frequency and voltage were stable, and operated within the acceptable ranges; even after the initial transients during the formation of the unplanned islanded Microgrid. A reliable Microgrid communication link; such as optical fibre will be required to make the communication between the Microgrid controller, adaptive protection settings adjustments and DERMS to be effective and dependable.

This paper described the typical power system studies that is necessary to design and operate a Microgrid. The stability and regulation simulation results of an unplanned islanded Microgrid using a synchronous generator and a grid following current source inverter to regulate the frequency and voltage of the Islanded Microgrid was presented.

The identification of a set of rules and conditions to be checked during the various Microgrid operating states was elaborated. While some of the studies are not applicable to standalone Microgrids, the learnings from such studies can be used to trouble-shoot any potential Microgrid.

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