A Mathematical Formulation for Assessment of Power Quality in Microgrid

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Abstract—The electricity sector in India had an installed capacity of 233.929 GW as of December 2013. India currently suffers from a major shortage of electricity generation capacity, even though it is the world’s fourth largest energy consumer after United States, China and Russia. The utilization of renewable energy sources such as solar power, wind power, biomass power etc. play a dominant role in electricity generation, with the increase in the global warming during recent years. Several advantages such as environmental friendliness, expandability, flexibility and controllability have made various renewable and nonconventional micro sources, an attractive option for configuring modern electrical grids. A microgrid consists of cluster of loads and distributed generators with their energy storage equipments. It operates as a single controllable system for the whole system. As an integrated energy delivery system microgrid can operate in parallel with or isolated from the main power grid. The microgrid can be designed to meet the special requirements such as enhancement of local reliability, increased efficiency and stability.

In this paper, a new mathematical formulation is presented, which facilitates the analysis of power quality of the energy storage system of a microgrid to which “n” number of units are connected. The new formulation reduces the complexity in analyzing the power quality of various units. This paper will help the power system planners to know at which point of time the particular unit does not show the effective operation and several essential steps can be taken to improve the power quality of the system, when the microgrid energy storage system is in operation. The practical results show that this formulation is true and applicable for all reserve capacities of microgrid with “n” units in operation.

Keywords— Renewable Energy Sources, Microgrid (Intelligent Grid), Inverter, Energy Storage Unit, AC Loads.

I. INTRODUCTION

Energy is the key to economic development and sustenance of future world. Energy demand in India as well as in many other countries across the world is ever increasing and expected to grow in future. The demand for power has increased more rapidly than its availability. In addition to shortage of power and energy demand for the existing consumers, there is around 1.44 billion population in the world without any access to electricity, out of which around 288 million reside in India.

Against this backdrop, Distributed Generation based power solutions have been considered as one of the feasible options, where, Distributed Energy Resources can not only deliver power to the local areas (where, it is installed and distributed) more efficiently and reliably, but it can also feed excess power, if any, to the utility grid. In addition, these systems are environmentally benign [1]. For many years there has been an ideal that inexpensive energy was only the main concern which affects customers; owners only cared about the electricity bills and nothing else. As long as it was cheap, no one seemed to mind. However because of the high upfront cost of renewable, designers and owners are attempting to reduce energy usage in order to get the most out of limited resources.

A microgrid as a localized grouping of electricity sources and loads that normally operate connected to and synchronous with the traditional centralized grid (macro grid) but can disconnect and function autonomously as physical and/or economic conditions dictate. There are various advantages offered by microgrids to end-consumers, utilities and society, such as: improved energy efficiency, minimized overall energy consumption, reduced greenhouse gases, polluting emissions, improved service quality, reliability and cost efficient electricity infrastructure replacement [2]. Technical challenges linked with the operation and controls of microgrids are immense. Ensuring stable operation during network disturbances, maintaining stability and power quality in the islanding mode of operation necessitates the improvement of sophisticated control strategies for microgrid’s inverters in order to provide stable frequency and voltage in the presence of arbitrarily varying loads [3]. In renewable energy resources and storage devices are connected to DC bus with different converter topology from which DC loads can get power supply. Inverters are implemented for power transfer between AC and DC buses. Common and sensitive loads are connected to AC bus having different coupling points. During fault in the utility grid, microgrid operates in islanded mode. If in any case renewable source can’t supply enough power and state of charge of storage devices are low microgrids then disconnects common loads and supplies power to the sensitive loads [4].
In this paper, power quality assessment has been done in case of islanding mode when renewable energy source can’t supply power and charge of storage devices are decreasing. Hence with this information, the proposed formulation can be utilized to obtain the power quality of storage device as well as several units connected to microgrid.

II. MICROGRID

A microgrid is a cluster of interconnected distributed generators, loads and intermediate energy storage units that co-operate with each to be collectively treated by the grid as a controllable load or generator [5]. The main objective of its conception is to facilitate the high penetration of distributed generators without causing power quality problems to the distribution network. Another important objective is to provide high quality and reliable energy supply to the sensitive loads. A microgrid comprises of DC power generation (i.e. fuel cell, solar PV panels, or wind turbines), DC electrical storage (i.e. battery or super capacitor), DC power distribution (i.e. wiring and control), DC gadgets (i.e. laptops, telephones and satellite TV controllers), DC/AC loads (i.e. LEDs, bulbs, CFLs, fans etc). The micro sources are the primary energy sources within the microgrid. They may be rotating generators or distributed energy (DE) sources interfaced by power electronic inverters. The installed DE may be biomass, fuel cells, geothermal, solar, wind, steam or gas turbines and reciprocation internal combustion engines.

The connected loads may be critical or non-critical. Critical loads require reliable source of energy and demand stringent power quality. These loads usually own the micro sources because they require a continuous supply of energy. Non-critical loads may be shed during emergency situations and when required as set by the microgrid operating policies. The intermediate energy storage device is an inverter-interfaced battery bank, super capacitors or flywheel. The storage device in the microgrid is analogous to the spinning reserve of large generators in the conventional grid. They ensure the balance between energy generation and consumption especially during abrupt changes in load and generation. Another method of integrating energy storage to the microgrid is to install battery banks in the dc links of the inverters of the micro sources [6].

The microgrid can operate in grid-connected mode or in island mode. In grid-connected mode, the microgrid either draws or supplies power to the main grid, depending on the generation and load mix and implemented market policies. The microgrid can separate from the main grid whenever a power quality event in the main grid occurs [7].

The microgrid should disconnect when an abnormal condition occurs in the grid. It shifts to island mode of operation, and the microgrid is faced with the following issues:

II (A). Voltage and frequency management

The voltage and frequency are established by the grid when the microgrid is connected. When the microgrid islands, one or more primary or intermediate energy sources should form the grid by establishing its voltage and frequency, otherwise, the microgrid will collapse. Both voltage and frequency should be regulated within acceptable limits. If the frequency has dropped to an excessive low level, loads may be shed to hasten its recovery towards the nominal value.

II (B). Balance between supply and demand

If the microgrid is exporting or importing power to the grid before disconnection, then secondary control actions should be implemented to balance generation and consumption in island mode. If the connected load exceeds the available generation, demand side management should be implemented. Also, there should be enough energy storage capacity to ensure initial balance after an abrupt change in load or generation.

II (C). Power quality

The microgrid should maintain an acceptable power quality while in island operation. There should be an adequate supply of reactive energy to mitigate voltage sags. The energy storage device should be capable of reacting quickly to frequency and voltage deviations and injecting or absorbing large amounts of real or reactive power. Finally, the microgrid should be able to supply the harmonics required by nonlinear loads.

III. MATHEMATICAL FORMULATION

Let us consider “n” numbers of units (A,B,C,...n) are connected to the microgrid with its energy storage system and there average powers are (say) $P_A$, $P_B$, $P_C$,........$P_n$.

![Fig 1: Arrangement of “n” Units with Energy Storage System](image-url)
For obtaining the power quality of the system, we must consider “m” number of voltage levels of battery voltage, keeping in mind the following condition
\[ m = n + 1 \]

The successive voltage of each interval can be defined by
\[ V_s = \frac{V_{\text{MAX}} - V_{\text{MIN}}}{n} \text{ Volts} \]

As battery voltage reduces from its maximum voltage to minimum during its discharge process.
Voltage of mth level can be obtained by following formula
\[ V_m = V_{\text{MAX}} - \frac{(V_{\text{MAX}} - V_{\text{MIN}})(m-1)}{n}; m = 1, 2, 3, \ldots (n+1) \]

Where, \( V_{\text{MAX}} \) = Maximum Voltage of Battery at full charge condition.
\( V_{\text{MIN}} \) = Minimum Voltage of Battery at full discharge

III. (A) Formulation for Inverter Operation

Inverters are employed for the purpose to obtain AC power from DC power of battery. The operation of an Inverter contains following two processes:

1) Oscillation
2) Transformation

Battery input voltage is applied to the Oscillator whose output is applied to the secondary winding of the transformer which is used to step up the DC voltage of battery to a required AC output voltage. This AC output is obtained at the primary of the transformer.

Let us consider DC voltage of the battery to be \( V_{\text{DC}} \), AC output of Inverter to be \( V_{\text{AC}} \) and transformer turn ratio is \( N_p/N_S \).

The following relationship will always be followed for “m” voltage levels of battery voltage
\[ \left( \frac{V_{\text{AC}}}{V_{\text{DC}}} \right)_m = \frac{N_p}{N_S} = \text{Cons tan t}; m = 1, 2, 3 \ldots (n+1) \] (I)

Where, \( N_p \) = Number of turns in primary winding
\( N_S \) = Number of turns in secondary winding

III. (B) Formulation for Voltage across n units
Voltage across n units (A, B, C........n) is given as follows:

At full battery level:
Voltage drop across unit A:
\[ V_A = V_{\text{AC}(m)} - V_d \] (1)
Where, \( V_d \) = Voltage drop across wire between AC output of inverter and Unit A.

And voltage of nth unit is:
\[ V_n = V_{n-1} - V_{d_n}; n = 2, 3, 4,\ldots \] (2)
Where, \( V_{d_n} \) = Voltage drop across wire between nth unit and (n-1)th unit.

Voltage at n units at mth level can be obtained by:
Voltage drop across unit A is
\[ V_A = V_{\text{AC}(m)} - V_d; m = 1, 2, 3, \ldots (n + 1) \] (3)
Note: \( V_{\text{AC}(m)} \) can be found from equation (1).
Voltage drop across nth unit is
\[ V_n = V_{n-1} - V_{d_n}; n = 2, 3, 4,\ldots \] (4)

III. (C) Formulation for current in n units
The AC current flowing in n units (A, B, C........n) can be given as follows:
At full battery level:
Current flowing in unit A is given by
\[ I_A = \frac{P_A}{V_A \text{Cos} \Phi} \] (5)
Where, \( \text{Cos} \Phi \) = Load Power Factor
And current in nth unit is given by
\[ I_n = \frac{P_n}{V_n \text{Cos} \Phi}; n = 2, 3, 4,\ldots \] (6)
At mth voltage level of battery:
Current in unit A is given by
\[ I_A = \frac{P_A}{V_{A_m} \text{Cos} \Phi}; m = 1, 2, 3\ldots(n + 1) \] (7)
And current in nth unit is given by

$$I_n = \frac{P_n}{V_n \cos \Phi}; n = 2,3,4... \tag{8}$$

Total Current in n units is given by

$$I_{total} = I_A + I_B + I_C + ... + I_n \tag{9}$$

IV. EXPERIMENTAL WORK

The above mentioned formulation has been verified by experimental work which was carried out with Battery Model no LES70TT, rated 150AH, 12 Volts, Inverter Model no HUPSD PLUS 700VA, serial no 11070195 and four AC loads or units of 1) 200watts, 250volts, 2) 100watts, 230volts, 3) 60Watts, 230volts and 4) 40watts, 230volts. Maximum and minimum voltage of battery in the period from full charge to discharge is taken 12.6 Volts and 10.6 Volts respectively. Operating turn ratio of inverter transformer is 17.5. All of the units are resistive due to which unity power factor operation ($\cos \Phi = 1$) is achieved and the power quality of these units is practically obtained. The operation is done two times for the accurate results with $\pm 10\%$ error.

Note: The formulation based data obtained for 200w, 250volts rated unit is somewhat differing because supply voltage is 230volts, not 250volts.

V. EXPERIMENTAL RESULTS

It is seen and verified that experimental results are according to the formulation which was developed for “n” unit operation. The result of the experiment is shown in table (I) and few pictures of readings are also attached.

<table>
<thead>
<tr>
<th>Battery Voltage</th>
<th>Inverter Output</th>
<th>Unit 1 (200w)</th>
<th>Unit 2 (100w)</th>
<th>Unit 3 (60w)</th>
<th>Unit 4 (40w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (Volt)</td>
<td>I (Amp)</td>
<td>V (Volt)</td>
<td>I (Amp)</td>
<td>V (Volt)</td>
<td>I (Amp)</td>
</tr>
<tr>
<td>12.6</td>
<td>221</td>
<td>220.9</td>
<td>0.76</td>
<td>220.3</td>
<td>0.43</td>
</tr>
<tr>
<td>12.2</td>
<td>212</td>
<td>211.7</td>
<td>0.74</td>
<td>211.1</td>
<td>0.40</td>
</tr>
<tr>
<td>11.6</td>
<td>203</td>
<td>202.2</td>
<td>0.72</td>
<td>201.8</td>
<td>0.39</td>
</tr>
<tr>
<td>11.1</td>
<td>194</td>
<td>193.0</td>
<td>0.70</td>
<td>192.6</td>
<td>0.38</td>
</tr>
<tr>
<td>10.6</td>
<td>184</td>
<td>183.0</td>
<td>0.69</td>
<td>182.6</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Fig 2: Block Diagram of Tested System

Fig 3: Practical Work
Fig 4: A Few Pictures of Experimental Results

Characteristics are also drawn

Figure 5: Experimental Current Distribution with time

Figure 6: Experimental Power Quality Assessment

Table II
Resistance Of Wires In Operation

<table>
<thead>
<tr>
<th>Wire Between two Nodes</th>
<th>Resistance (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC supply and Unit 1</td>
<td>0.7</td>
</tr>
<tr>
<td>Unit 1 and Unit 2</td>
<td>0.5</td>
</tr>
<tr>
<td>Unit 2 and Unit 3</td>
<td>0.3</td>
</tr>
<tr>
<td>Unit 3 and Unit 4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table III
Results Based On Formulation

<table>
<thead>
<tr>
<th>Battery voltage</th>
<th>Inverter Output</th>
<th>Unit 1 (200w)</th>
<th>Unit 2 (100w)</th>
<th>Unit 3 (60w)</th>
<th>Unit 4 (40w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (Volt)</td>
<td>I (Amp)</td>
<td>V (Volt)</td>
<td>I (Amp)</td>
<td>V (Volt)</td>
<td>I (Amp)</td>
</tr>
<tr>
<td>12.6</td>
<td>220.5</td>
<td>219.4</td>
<td>0.70</td>
<td>219.0</td>
<td>0.41</td>
</tr>
<tr>
<td>12.1</td>
<td>211.7</td>
<td>210.7</td>
<td>0.67</td>
<td>210.3</td>
<td>0.40</td>
</tr>
<tr>
<td>11.6</td>
<td>203</td>
<td>202.0</td>
<td>0.65</td>
<td>201.6</td>
<td>0.38</td>
</tr>
<tr>
<td>11.1</td>
<td>194.3</td>
<td>193.3</td>
<td>0.62</td>
<td>192.9</td>
<td>0.37</td>
</tr>
<tr>
<td>10.6</td>
<td>185.5</td>
<td>184.6</td>
<td>0.59</td>
<td>184.3</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Fig 7: Formulation Based Current Distribution with Time
Therefore, by power quality analysis, further required steps can be taken if any of the unit is found to be affected at any point of time when storage of microgrid is degrading with time so that the stable and reliable operation of the system can be maintained to improve the efficiency of the microgrid with desired capacity of the energy storage system.

REFERENCES


