A NOVEL APPROACH FOR LOAD FLOW AND FAULT ANALYSIS IN MICROGRIDS

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***Abstract*—Due to the advantages of renewable power generation and its simplicity, the growth of them are increasing around the world. Three main value propositions have been identified for micro grids in this work: improving reliability through islanded operation during outages; providing revenue in grid connected operation; and improving power quality by rapidly islanding during utility disturbances and outages. Inverter interfaced distributed generators (DGs) in micro grids have different characteristics and models that are not available in the existing conventional power flow analysis tools. This paper presents a static modeling approach for inverter interfaced DGs that can be applied for time spread load flow analysis and fault analysis of micro grids, including droop-based voltage controlled DGs. Providing improved power quality through seamless islanding is challenging and costly when trying to compete with existing power-quality solutions. The static models have been derived from the common control schemes applied to inverter interfaced DGs, including the constraints emerging from droop control and reflect steady-state behaviors of inverters accurately. In addition to simplification of analysis procedure, the static models can provide a base for the analysis of micro grids with conventional numeric analysis tools. The presented static modeling approach has been validated comparatively with the dynamic modeling MATLAB/simulink simulation results of a test micro grid.**

Index Terms - Droop control, Fault analysis, Inverter, Load flow, Micro grid, Static modeling.

I. INTRODUCTION

Conventional analysis methods to Current Controlled (CC) DGs with limited fault current. Although the approaches seem appropriate for CC DGs in grid connected operation, they do not address Voltage Controlled (VC) DGs in the islanded operation of the micro grids. The fault models of DG inverters under voltage control scheme can be applicable to single-master operation of micro grids. Multi-master operation of micro grids based on droop control requires more comprehensive models of DGs for the analysis of islanded micro grids. Proposes a static modeling approach, which is implemented with phasor simulation method, for inverter interfaced DGs to be applied in load flow analysis of micro grids including faults. The analysis method can be applied for both grid connected and island mode of operation. The limitations are applied to DG currents instead of powers and the effects of the output filter capacitors are also included in the developed analysis method.

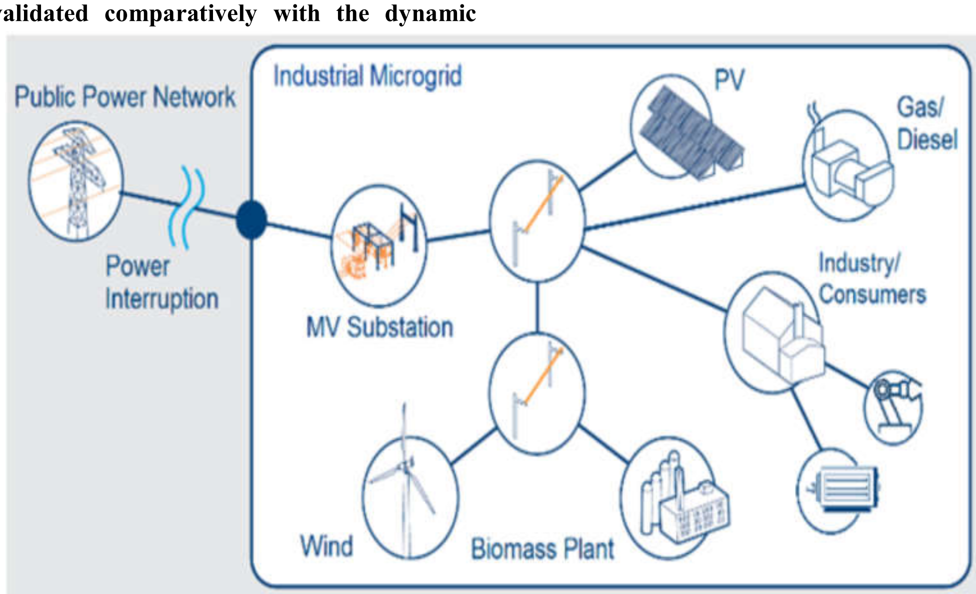

Fig: 1. A typical MG connected to the public power grid

To simplify the application procedure especially for time spread load flow analysis, the analysis method has been implemented with the phasor simulation method of Matlab/Simulink using a generic source model. The objective of this research is to mitigate inverter overloads caused by poor transient load sharing between inverters and synchronous generators in islanded micro grids. The cause of the poor transient load sharing characteristics is investigated and the use of virtual impedance and transient droop are proposed to control the transient load sharing characteristics. Inverter current-limiting in the presence of synchronous generators is investigated and virtual impedance current limiting is proposed to provide stable current limiting during overloads. Finally, current limiting during three-phase faults is investigated.

Fault contribution from DG may be sufficient to allow satisfactory operation of protection systems. DG may be able to regulate the voltage and frequency within the islanded system. The parallel operation of DG units within the island may not be cause problems. Unsynchronized, out-of-phase reclosing may not be occurring when the islanded distribution is reconnected to the distribution system. The operating DG units to detect grid problems and to subsequently disconnect the DG units from the grid within a maximum of 2 seconds.

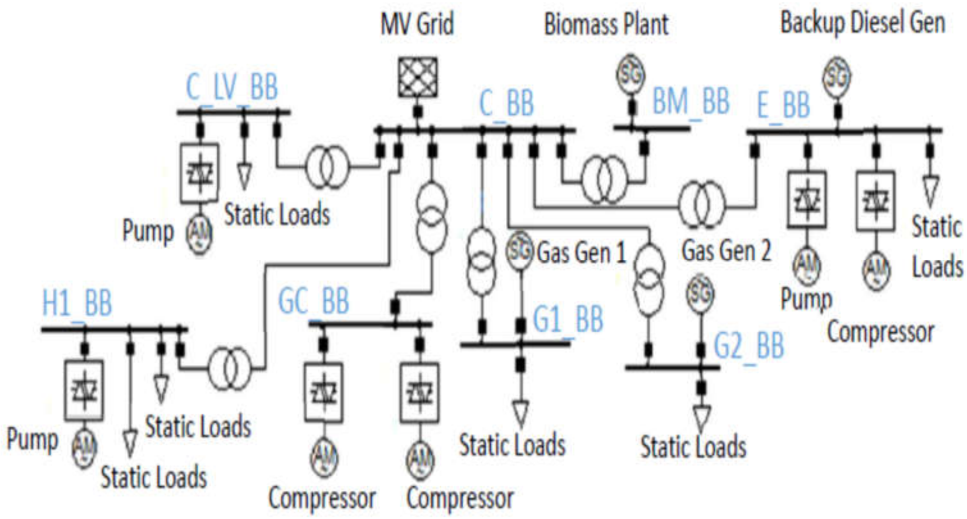

Fig: 2. Schematic of the modeled micro grid with 20/0.4 kV network and various DG units and load

Micro grids can be regarded as special applications of active distribution networks. In distribution networks high sub transient fault current components that are seen in the fault currents of transmission systems are not observed. Therefore, fault currents of the micro grids can be approximated by their steady-state values. Based on this consideration, this paper proposes a static modeling approach, which is implemented with phasor simulation method, for inverter interfaced DGs to be applied in load flow analysis of micro grids including faults. The analysis method can be applied for both grid connected and island mode of operation. The limitations are applied to DG currents instead of powers and the effect of the output filter capacitors is also included in the developed analysis method.

II. DISTRIBUTED ENERGY RESOURCES AND MICROGRIDS

DG technologies typically include wind turbines, solar photovoltaic (PV) systems, fuel cells, small hydro, micro turbines and other cogeneration plants. These DGs along with distributed storage systems such as batteries, super capacitors have formed the concept of distributed energy resources (DERs) which are usually connected to the medium voltage (MV) or low voltage (LV) grid within the distribution system. DERs are being increasingly integrated as a means of power supply into the distribution system as opposed to reliance on bulk supply points from traditional centralized power plants. Environmental factors such as limiting the greenhouse gas (GHG) emissions and avoiding the investments of new transmission networks and large generating plants have been the primary motives behind the growth of DERs. DERs have begun to feature active characteristics in the distribution networks with bidirectional power flows, converting the passive networks into active distribution networks. DERs can be divided into two groups in terms of their interfacing mechanism with the micro grid. One group includes rotating machines that are directly coupled to the micro grid, while others are coupled through power electronic interfaces. Therefore, the control concepts and power management strategies used in a micro grid comprising both inverter and non-inverter interfaced DERs are significantly different from those of a conventional power system. Different hierarchical control strategies are adopted at different network levels in order to achieve better coordination among the DERs and the local loads. The control strategies must allow the micro grids to operate in islanded mode due to faults or any other large disturbances in the external grid. In grid connected mode, micro grids may export/import active and reactive power to/from the utility grid depending on their primary objective.

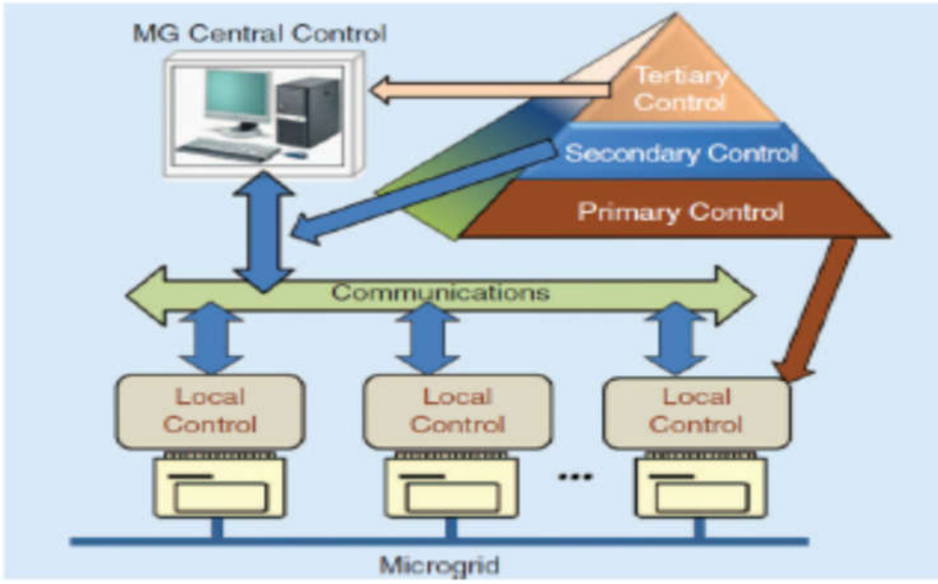

Fig: 3. Micro grid control levels

A hierarchical control of microgrids has been proposed recently to standardize micro grid operation. As illustrated in Fig.3, at the bottom level, a primary controller is responsible for protection functions, local voltage control and power sharing management among multiple DERs to ensure system reliability. At the next level, the secondary controller restores micro grid frequency and voltage either by communicating with the MCC in a centralized manner or by using multi- agent systems in a decentralized manner. The tertiary controller at the top level carries out the economic optimization based on the energy prices and market operation. Furthermore, the tertiary controller can communicate with the DNSP in order to optimize micro grid operation with the utility grid. In order to carry out successful operation of micro grids, it is vital to have a proper communication methodology. Communication in micro grids is being carried out based on radio communication, through telephone lines, power-line carrier or using a wireless medium (internet and global system for mobile communication).

III. SYSTEM MODELING

A micro grid, which has a generic schematic diagram as shown in Fig. 4, has two main operational mode; grid connected and island. In each mode micro grid DGs has corresponding control implementations. In grid connected mode all DGs are controlled with current control scheme. Depending on the type of the source in terms of being intermittent (PV, wind) or non-intermittent, DC link voltage regulation or PQ based current control schemes are the accepted common current control approaches respectively, applied to the micro grid DGs in grid connected mode. Note that, DC link voltage based current control regulates the DC link voltage at maximum power point with a very low control bandwidth (1 Hz). Therefore, it can also be termed as PQ control where P set value ($P*$) corresponds to the available instant renewable source power. In island mode, non-intermittent type DGs return to a droop based voltage control while intermittent DGs (and storage units if exist) continue to operate with current control scheme to extract the maximum available power.

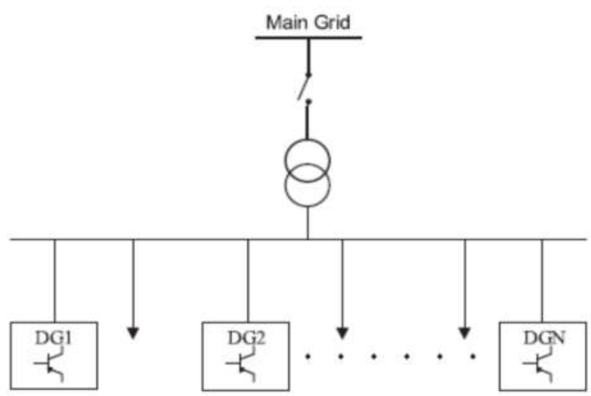

Fig: 4. Schematic diagram of a generic micro grid.

In Fig. 5(a) and (b), control block diagrams of the current control and voltage control schemes together with single line electrical diagram of the inverters are presented, respectively. There exists an LC filter at the output of DG inverters. It needs to be pointed out that transition between the operational modes of the micro grids requires switching between the aforementioned control schemes for the relevant DGs. In case of an unintentional islanding, fast islanding detection plays a critical role for proper operation of the micro grid. It is also to be noted that the modified droop control schemes proposed for soft transition like those in have the same respective steady-state behavior in each mode and can be handled in the same content as the control schemes presented here. In both current control and voltage control schemes, current controller and current limiter are the common blocks with similar implementations. Current limiter is one of the critical control implementations that affect the fault response of DGs. Some possible current limiting strategies for CC DGs are described. It should be noted that in static modeling the matter of interest is the steady-state behavior of the current limiting strategy applied. For VC DGs the same current limiting strategies can be applied. In this case, however, since the current references are produced by the voltage controller in a closed loop (see Fig 5 (b)), anti wind-up and latch-up strategies should be taken into consideration.

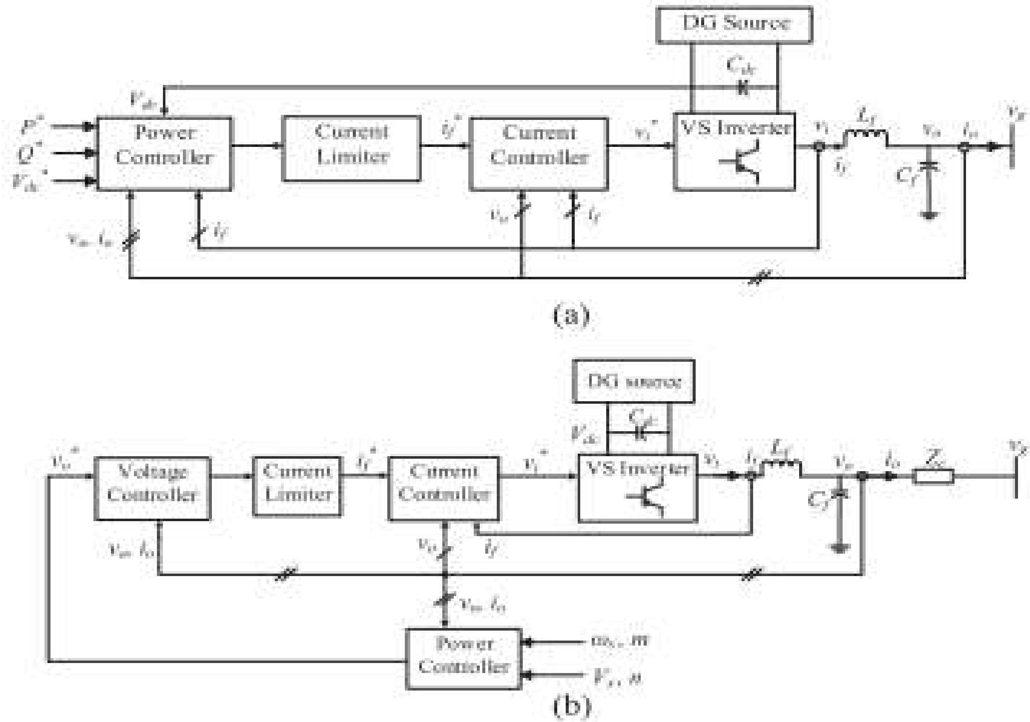

Fig: 5. Micro grid DGs control implementations. (a) Block diagram of current control scheme. (b) Block diagram of voltage control scheme.

The voltage controller in voltage control scheme and the current controllers in both schemes can be implemented in either synchronous *dq* frame, stationary *αβ* or natural *abc* frame. The common approach is use of PI controllers with additional feed-forward compensation, implemented in synchronous *dq* frame. The coupling impedance *Zc* shown in the block diagram of the voltage control scheme in Fig. 5(b), is required for stability of islanded micro grids and intentionally placed to provide enough stability margin for LV micro grids that have negligible line impedances. It can be implemented either physically or virtually by proper control implementations. Power controllers, on the other hand, dictate the main characteristics of steady-state behaviors of VC and CC DGs. They are dealt separately in the following parts in connection with corresponding steady-state behaviors of DGs for both control schemes.

IV. SIMULATION RESULTS

Case-1: Fault analysis of islanded micro grid

In this case, the micro grid is islanded and two equivalent droop controlled inverters (DG1 and DG2) are also added to the micro grid, located at distribution transformer substation. In addition, there exists a consumer PV inverter connected to Bus 3. Note that, location of islanding switch at the high voltage side of the distribution transformer is advantageous for safety reasons. Inverters have a nominal power of 5 kVA with a peak current limit of 40 A (twice the rated current), and are operating at rated power before the fault is applied. The fault is three-phase to ground fault with a ground resistance of 1Ω, applied at t=0.6s at Bus 6 as shown. The threshold fault voltage level for VC DGs to switch to the current limiting mode has been set as Vf = 160 V. Under these conditions, static modeling analysis results for droop controlled inverters and PV inverter output currents before and after the fault have been obtained as follows(Table-1).

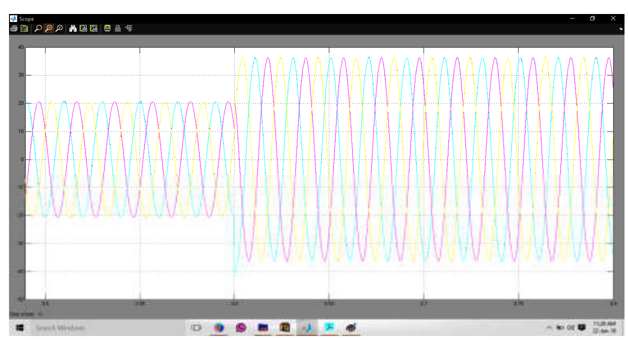

Fig: 6. Dynamic simulation results for droop controlled inverter currents.

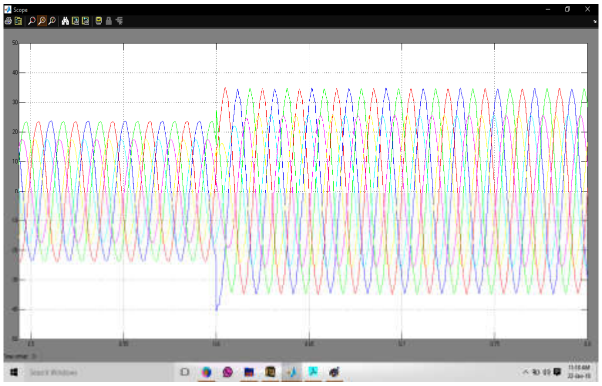

Fig: 7. Dynamic simulation results for PV inverter current.

The current values obtained above indicate that the droop controlled inverters have been subjected to current limiting after the fault whereas current level of PV inverter has not reached limit level. Dynamic simulation results, on the other hand, for the droop controlled inverters and PV inverter is presented in Figs. 6 and 7, respectively. For comparison, static analysis results for PV inverter current before and after the fault is superimposed on the dynamic analysis result in Fig. 6. As seen, the static analysis model determines the steady-state values of dynamical elements quite successfully. Since PV inverter reference current is low pass filtered, output current settles down with a delay and performs some oscillations after the fault, but finally reaches the expected steady-state value.

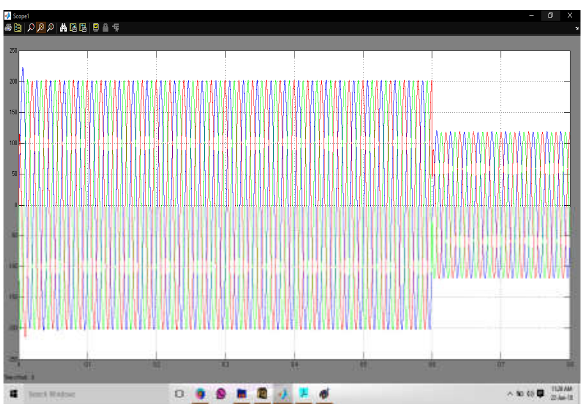

Fig: 8. Grid voltage (Bus 1) when current limiting is not applied to the inverters.

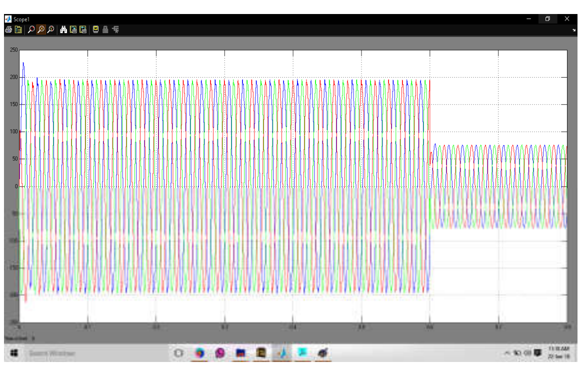

Fig: 9. Grid voltage (Bus 1) when current limiting is applied to the inverters.

Figs. 8 and 9 present dynamic simulation results of the Bus 1 voltage for the cases with and without current limiting applied to the inverters, respectively. Note that, Bus 1 node is the point beyond the coupling impedances of droop controlled inverters whose voltage is used to detect fault condition and corresponding current control mode in static models of voltage controlled inverters. Without current limiting, grid voltage reduces from 200 V peak to 125 V peak with an inverter output current of 75 A peak. Note that the threshold voltage must be high enough to detect current limiting mode accurately (it needs to be higher than 125 V in this case) but low enough to distinguish the normal operation condition from the faulty condition. The accurate threshold voltage value can be determined with a two-step solution. In the first step, VC DGs are included to the system without current limiting. If currents of VC DGs exceed their limit values then in the second step they are included with current limiting with a threshold voltage determined according to the output voltages of the first step. It should be noted that if droop coefficients are arranged so as to provide proportional power sharing between the VC DGs, then all droop controlled DGs are expected to switch to current limiting mode simultaneously. Current limiting, on the other hand, dramatically reduces the fault voltage levels in the micro grid. Note that, this extra voltage reduction emerging from current limiting can be used for fault detection in micro grid protection systems as an alternative to the conventional over-current based fault detection methods.

V. CONCLUSION

Micro grid inverters present specific steady-state behaviors due to their specific control features such as droop control and current limiting that cannot be processed with the conventional power flow analysis tools. Analyzing the network with dynamic models, on the other hand, is quite compulsive and takes too long time due to computational burden and complexity as the network enlarges. In this study, it has been shown that static equations of an islanded micro grid, including droop based DG inverters, has enough constraints to be solved by numeric methods. Then, by using phasor simulation method it has been shown that developed static models for DG inverters, based on the constraints of droop control and current limiting, can be used to perform power flow analysis of small to medium scale micro grids including faults. The developed static models also include practical aspects of DG inverters such as current based limiting instead of powers and effects of output filter capacitors. Static modeling with phasor simulation method facilitates the time spread load flow analyses considerably. The convergence of the phasor simulation method has pointed out that the proposed droop and limit current constraints provide enough conditions for the analysis of large micro grids using numeric methods, as well. On the other hand, the detection of current limiting requires a special consideration due to the lack of a current reference information in power controller of the voltage controlled DGs. As a solution, a grid voltage based current limiting detection has been proposed, where threshold voltage can be determined with a two-step solution. It has been shown that the proposed method serves the purpose in case of symmetrical faults.

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