A Novel Power Management Scheme for Distributed Generators in a DC Microgrid

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Abstract. The energy management scheme is a desirable solution to integrate multiple renewable energy generators into the network and operate them synchronously. Controlling the energy shared between different distributed generators is an important consideration for the stabilized operation of the electricity grid. In this thesis work, a new method with the concept of fall control technique is used and is designed to control the power of each individual generator in the particular DC network. The proposed energy management scheme can be widely applied to the grid connected to the grid and to the grid isolated from the electricity grid to obtain high energy distribution efficiency and also provide greater stability. An efficient power control method for sharing the power required by the load is designed based on the drop control concept. The proposed controller can be applied to a single distributed generator to adjust its output power quickly and accurately. The power sharing control method was formulated, modeled and verified by simulating transient stability and steady state test studies. The optimal coupling resistance for power sharing was also identified. Controller interaction and communication delay were also investigated. Communication delay interference is negligible for the shared power controller. The system is simulated in the MATLAB / SIMULINK environment.

Keywords: DC micro grid, grid, power management, simulation, droop control.

1. Introduction

Now-a-days, the use of renewable energy has increased due to environmental concerns and increased price of fossil fuels. Continuous development in industrial and commercial sectors has become a burden to the traditional power grid and hence the demand for renewable resources integrated grid systems has increased. Traditionally, alternating current is being used due to its ability of stepping up and stepping down of the voltage based on the needs at the load end. Recently in the field of electric power generation, transmission and distribution, the use of DC power has drastically increased. The aim of the thesis is to integrate the DC power network with the AC power network and not the replacement of AC with DC.
Figure 1. Integration of DC and AC Power Network

Fig.1 shows the integration of the DC and the AC network, where the DC distributed generators and the AC generating systems are connected to the same grid network. The DC distributed generators require a DC-AC converter system to be integrated with the AC grid. When there is broader access to electricity, the efficiency of the transmission grid is found to be more balanced. When the demand increases, the generating capacity finds it difficult to meet the required demand. This could be rectified by installing microgrids with renewable energy sources as the primary source of electric power. Here, multiple generators are connected to a single microgrid to meet the demand at the load end of the microgrid. The microgrid also has access to be integrated with the traditional grid network. The integration of the distribution system enhances energy management, conversion efficiency and grid reliability [1, 2]. DC microgrids are currently in trend as the renewable energy generators can be used as the primary source of power efficiently [1, 2]. The recent demand is for the photovoltaic and wind energy based DC microgrid systems. Remarkable development in the electronics technology has brought in power converters which can completely work on DC power. The load power demand is also exceedingly increasing for DC source. These strategies bring in high efficiency on the working of DC microgrid systems.

The proposed power management scheme for distributed generators in DC networks, has several advantages including improved efficiency and optimized synchronization over the previous converters. The system designed in the work can fit commercial renewable power networks. The working efficiency of the system is maintained by providing proper power sharing between the distributed generators connected to the DC system. Droop control is used as the principle to design the controller in each converter. The stability analysis is performed for the system designed. Testing of the model is performed using the MATLAB/SIMULINK software.

2. Concept of DC Microgrid

Microgrids can operate autonomously or can be grid connected and based on the type of power; it can be AC or DC. Tremendous advancement in the field of DC energy has led to the introduction of the DC microgrids in the power network. The DC microgrids have better efficiency and compliance with the customer electronic loads as well [1,8]. The microgrids usually tend to use renewable energy as their primary source of power. Droop control is used for the voltage control and regulation in the converters and generators connected to the microgrid. The DC microgrids has proved to provide added efficiency and reliable energy transfer [3]. The use of DC distribution system has become outspread due to their harmonic management and synchronization [1-2]. The reliability of the network is ensured by integrating it with the main power grid. Since there are power electronic AC-DC and DC-AC converters, it
makes it accessible for the integration of the microgrid with the traditional AC grid as well. Figure 2 shows the DC Microgrid block diagram.

The DC distribution enhances the incorporation of renewable energy sources as it eliminates conversion and saves 2.5% to 10% of the generated energy. Uninterrupted power supplies are conveniently reliable using DC power as it can be easily backed up to the energy storage systems such as batteries [4]. The DC distribution system enhances the voltage stability during the co-existence and integration of the DC with AC systems, which is usually carried out by the reactive power optimization in the integrated AC system[7-12]. The power quality converters using DC source boosts the power quality standards as the first stage of DC supply offers power factor correction in the AC integrated network[4-6].

3. Existing Power Management Schemes
The distributed generators based DC systems are integrated with the main AC grids to avoid the occurrences of blackout and instability. By integrating, the excess power generated by the distributed generators can be injected to the main grid. This in turn helps the consumers to sell the excess generated electric power from their microgrid systems. The power sharing between the different generators is crucial as it maintains the stability within the entire grid system. The power demand has to be met by the generators equally. If a generator is not in full load working condition, the other generators must be able to meet the power demand by proper power sharing between them. The power demand has to be met by the generators even when the system is experiencing instability. Instability occurs due to sudden increase or decrease in load connected to the network, lack of a generating unit, etc. The system has to provide efficient power sharing even during the absence of a backup storage system. The power sharing is usually carried out by using a battery source as a backup to supply power during an interruption in the generating systems. The battery sources cannot withstand the higher power demand for a longer period of time. This can only be rectified by proper power sharing between the generators, the grid and the backup sources.

Power sharing is performed also by using current sharing techniques by maintain the voltage constant throughout the system. A common current sharing method is the master-slave current sharing scheme which allows to generate effective reference voltage value among the converters [5]. A current sharing compensator is used in the current sharing loop which generates a signal proportional to the difference between the converter voltage signal under consideration and the reference signal. The main disadvantage of this master slave technique is that the entire system is shut down to generate the reference signal value[5].

In recent times, droop control based power sharing techniques are used where a virtual output impedance is set on each connected converter. Droop constant or a virtual impedance is set for each converter to act as the reference values [6, 15-18]. This technique also makes use of the droop gain for the control of power sharing among the generators. The slope of the load regulation is determined to provide the voltage regulation and the power sharing control among
the generators using the droop current sharing technique [7]. A feedback signal proportional to the output current is generated to modify the output voltage loop characteristic. The maximum droop range is also calculated to maintain the droop value within the reference value. The droop based power sharing techniques follows three control methods, namely, centralized, decentralized, and distributed systems. The main limitation of the droop based power sharing technique is the poor voltage regulation occurring due to the high droop gain produced [18]. The main disadvantages of the existing power sharing systems include poor load sharing and circulating current between the converters.

4. Power Management Scheme with Droop Control

The design of a novel droop controller in particular for DC networks including their role in power sharing control. Originally applied to AC networks, droop control is used to maintain the rated voltage across the system[8]. Power sharing and control is sustained by maintaining the voltage constant throughout the operation of the system. The ability of the generators to perform efficient power sharing is controlled by the controller of each converter. The DC-DC converters (Fig. 3) acts as the interface for power sharing for each generator with the grid and the load connected to it. The effect of power sharing on the stability of the system is higher. This model is designed to withstand the crucial effects of instability occurring at each generator-converter unit. A DC-DC converter is used as an interface between the photovoltaic source and the load or the grid system. A coupling resistor is used to connect the converter to the external grid or the output load to provide proper stability to the system. The designed system can be operated in any percentage of the load based on the power demand at the load end of the system. This is obtained by controlling the current required for the specified power demand as the voltage is always maintained constant. The droop controller is used to maintain the voltage constant and to regulate the power based on the demand in the DC network. The basic idea is to regulate the output voltage of the converter so as to maintain the desired load power. By regulating the output voltage of the converter, the output current to the load and to the coupling resistor can be controlled, thus, regulating the output power to the grid based on the load percentage requirement.

![Figure 3. Block Diagram of Proposed Model](image)

The entire model is designed based on the fact to maintain the voltage droop to less than 4%. Fig. 4 represents the droop curve of the proposed model. The x-axis represents the output power or the load power of the system. This indirectly represents the load current or the output current as the voltage across the entire system is maintained constant throughout. The y-axis represents the output voltage of the converter. Two points $P_1$ and $P_2$ are marked on the graph. When there is no output current, the system is designed to maintain 4% higher droop in voltage and when the system is at rated power, the voltage is also at rated condition. The output voltage at the converter end is dependent on the droop value. From the droop curve, it can be seen that as the output power of the system changes from 0 to the rated value, the output voltage of the converter changes from $m^*V_{ob}$ to $V_{ob}$. 


The droop equation is obtained by deriving the relation between the output power or the load power \( P_{\text{out}} \) and the output boost converter voltage \( V_{\text{ob}} \).

\[
\frac{P_{\text{out}}}{V_{\text{ob}}} = I_{\text{out}} = I_{\text{ob}} = \frac{V_{\text{ob}} - V_{\text{out}}}{R_{\text{coup}}} \tag{1}
\]

Where,
- \( P_{\text{out}} \) is the output power or the load power
- \( V_{\text{ob}} \) is the output voltage or the load voltage
- \( V_{\text{out}} \) is the voltage at the output side of the boost converter
- \( I_{\text{out}} \) is the output current or the load current
- \( I_{\text{ob}} \) is the output current of the boost converter
- \( R_{\text{coup}} \) is the coupling resistance added between the boost converter output side and the load

\[V_{\text{ob}}\text{is derived as a function of } P_{\text{out}}.\]

\[
V_{\text{ob}} = f(P_{\text{out}}) = f(I_{\text{out}}) \tag{2}
\]

Hence, the droop equation is derived as a function of the output current as the output voltage is maintained at the rated value throughout.

The droop controller is designed based on the following equation,

\[
V_{\text{ob}} = (V_{\text{out}} + V_{\text{dropbase}})[1 + m(1 - \frac{I_{\text{out}}}{I_{\text{out,req}}})] \tag{3}
\]

Where,
- \( V_{\text{dropbase}} = I_{\text{out,req}} R_{\text{coup}} \)
- \( m \) is the droop factor
- \( I_{\text{out,req}} \) is the required load current

Here, \( V_{\text{dropbase}} \) is a calculated value and not a measured value. \( I_{\text{out,req}} \) is a value given to the controller based on the load percentage required, i.e., when the requirement is full load, then \( I_{\text{out,req}} = I_{\text{rated}} \) and when the requirement is half load, then \( I_{\text{out,req}} = I_{\text{rated}}/2 \) and so on. Here, the calculated output voltage of the boost converter is the reference voltage for the calculation of the duty cycle value. Hence, the droop equation controls the proper power sharing between the converters. The converter output voltage changes based on the change in the coupling resistance, the connected load and the power demand of the entire system. When the load connected to the system changes, the load current changes and hence there is a change in the converter output voltage. The droop value can be considered as a function of the load current considering negligible coupling resistance.
5. Modelling & Simulation Results

Case (i) Single unit DG: Simulation has been performed using the MATLAB/SIMULINK software. Fig.5 shows the Simulink model of single unit distributed generator. The input source is considered to be the PV source and the output voltage source represents the grid connection to the converter. The coupling resistor acts as the interface between the converter and the grid system. The value of inductors and capacitors connected in the system are calculated using the duty cycle calculation. The measured values of voltage and the current output is given to the droop controller block for the generation of the required converter output voltage signal. This signal is in turn given to the duty cycle generator for the duty cycle signal generation, which is given as the switching signal to the connected MOSFET switch in the DC-DC converter.

The value of the capacitors and inductors connected to the system are calculated as follows,

\[ M(D) = \frac{V_{dc}}{V_{in}} = \frac{1}{1-D} \quad (4) \]

From eq(1)

\[ D = \frac{V_{dc} - V_{in}}{V_{dc}} \quad (5) \]

The value of capacitance is calculated using the formula,

\[ C = \frac{D*V_{dc}}{2\Delta V_{dc} * R * f_s} \quad (6) \]

The inductance value can be calculated using the formula,

\[ L = \frac{D*V_{dc}}{2\Delta i_s * f_s} \quad (7) \]

The L and C values are calculated as above to maintain the rated voltage across the system by maintaining the calculated duty cycle.
The droop controller block (Fig. 6) is designed based on the droop equation generated. It generates the signal required for the duty cycle generation based on the load demand. The value changes based on the changes in the output load power. In the duty cycle generator block (Fig. 7), a PWM generator is used to generate the switching signal for MOSFET switch. The standard duty cycle equation is used to build the duty cycle generator block to avoid instability issues in the system. The duty cycle is given to the switch to enable the conversion operation of the boost converter. The components are designed to obtain rated values of output voltage and power.

Table 1: Parameters of the Single DG Unit

| Parameter Name | Value |
|----------------|-------|
| V_{grid}       | 400 V |
| V_{in}         | 220V  |
| R_{in}         | 0.001Ω|
| C_{in}         | 100nF |
| L_{in}         | 1.886mH|
| C_{out}        | 4.9μF |
| R_{coup}       | 10Ω   |

Figs. 8 & 9 represents the output waveforms of the single unit system. The per unit values are used to generate the waveforms. The base value of the output voltage of converter is 487.5V, output current of converter is 8.75A and output power of converter is 3.5kW. The single unit system generates the rated values of power for all types of load values. The coupling resistance changes based on the load connected to the system. The single unit system is connected to a grid at the load side. The output voltage of the converter has to be higher than the rated voltage to maintain the drop across the coupling resistance. Hence the output voltage of the converter is maintained at 487.5V. This in turn maintains the rated voltage and power of the single unit system. The primary peak of the voltage and power is negligible as it is maintained within allowable limits and the system then continues to maintain the rated voltage with the least harmonics.
Figure 8. Output Waveforms of Single Unit Generator in per unit values

Figure 9. Output Waveforms of Single Unit Generator in base values
Case (ii) Two single unit DG’s operating in parallel:

Two single unit systems are connected in parallel to the load and the grid system. All the values are similar to the single unit systems except for the grid and the load values. The parallel units based system is designed to meet the power sharing requirements (Fig. 10). The load power or the power demand is equally divided among the distributed generators based on the working conditions of the generators. The power is contributed equally by the generators when they are operating in full load conditions. When any of the generator experience maintenance or technical interruptions, it would only be able to generate load lower than the full load capacity. During this condition, the converter at full load generates the rated power and the remaining power demand is met by the other converter and the grid. As one of the converter’s capacity decreases, the input power from the grid increases to meet the power demand.

![Figure 10 Required Output Voltage Waveform of Converters](image)
Figure 11. Measured Output Voltage Waveform of Converters
Figure 12. Measured Power Waveforms of the Model
Fig. 11 represents the measured output voltage of the converter. The system shows only a drop of 2.11V between the required output voltage and the measured output voltage of the converter. The power sharing between the converters is entirely controlled by the droop controllers of the converters. This indicates that the calculated output voltage of converter is the key factor for the power control between the distributed generators. The base value of output voltage of the converters are taken as 487.5V to meet the voltage drop across the coupling resistance of 10Ω. The power output waveforms are represented in Fig. 12. The base values of the output power of each converter is taken as 3.5kW and the base value of the input power from the grid is taken as 3.0kW. The parallel converters exhibit equal power sharing among the converters. The converters operate at a full load condition delivering a power output of 3.5kW each. The load connected to the system is 10kW. And hence the remaining power is given to the system by the grid which is about 3.0kW. Even if there is an interruption in any of the converter system, the other converter shares the power efficiently and the remaining power is contributed by the grid. The performance of the system is analyzed by measuring the output current and power of each of the converter. The output current and power contribution of each of the converters connected to the load are equally shared and the system stability is maintained.

6. Conclusion

The power sharing between the distributed generators connected in a DC microgrid system is performed and analyzed. The working of the system is monitored by performing the steady state and the dynamic analysis for the system. The tests are performed for various values of the coupling resistance. This leads to a conclusion that the system efficiency and performance is not affected and also the system is optimized when the coupling resistance value is maintained above 0.3p.u. This helps in maintaining the rated system voltage of 400V throughout the working of the system by using the droop controller installed in each converter. Since the voltage is maintained constant, the power control can be easily carried out by controlling the output current from each converter. The system works with external and internal communication signal given to each converter by maintaining the stability within the limited range provided. This helps in eliminating the effect of instability and occurrence of blackouts. Theoretically, this novel power sharing control can be generally applied to any DC generators for their output power regulation.

References

[1] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, “DC microgrids—Part I: A review of control strategies and stabilization techniques,” IEEE Transactions on power electronics, vol. 31, no. 7, pp. 4876-4891, 2016.
[2] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, “DC microgrids—Part II: A review of power architectures, applications, and standardization issues,” IEEE transactions on power electronics, vol. 31, no. 5, pp. 3528-3549, 2016.
[3] A. Pratt, P. Kumar, and T. V. Aldridge, “Evaluation of 400V DC distribution in telco and data centers to improve energy efficiency,” in Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International, 2007, pp. 32-39: IEEE.
[4] D. J. Hamsterstrom, “AC versus DC distribution systems did we get it right?,” in PowerEngineering Society General Meeting, 2007. IEEE, 2007, pp. 1-5: IEEE.
[5] U. Nutkani, P. C. Loh, and F. Blaabjerg, “Cost-based droop scheme with lower generation costs for microgrids,” IET Power Electronics, vol. 7, no. 5, pp. 1171-1180, 2014.
[6] B. T. Irving and M. M. Jovanovic, “Analysis, design, and performance evaluation of droopcurrent-sharing method,” in Applied Power Electronics Conference and Exposition, 2000.APEC 2000. Fifteenth Annual IEEE, 2000, vol. 1, pp. 235-241: IEEE.
[7] J. Schonbergerschonberger, R. Duke, and S. D. Round, “DC-bus signaling: A distributedcontrol strategy for a hybrid renewable nanogrid,” IEEE Transactions on industrialelectronics, vol. 53, no. 5, pp. 1453-1460, 2006.
[8] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Wojte, J. Driesen, and R. Belmans, “A voltage and frequency droop control method for parallel inverters,” IEEE Transactions on power electronics, vol. 22, no. 4, pp. 1107-1115, 2007.
[9] Baig, K., Prudhvi Raj, K., Raja Sekhar, G. G., Vijay Muni, T., & Kiran Kumar, M. (2020). Power quality enhancement with active power control. Journal of Critical Reviews, 7(9), 739–741. https://doi.org/10.31838/jcr.07.09.143
[10] Bhargavi, R., Ganesh, P., Raja Sekhar, G. G., Prakash, R. B. R., & Muni, T. V. (2020). Design and implementation of novel multilevel inverter. Journal of Advanced Research in Dynamical and Control
[11] Muni, T. V., & Lalitha, S. V. N. L. (2020). Implementation of control strategies for optimum utilization of solar photovoltaic systems with energy storage systems. International Journal of Renewable Energy Research, 10(2), 716–726.

[12] Muni, T. V., Varma, P. S., Priya, S. K., Bhavya, J., & Rajasekhar, S. (2020). Energy management in a DC microgrid with energy storage system. Journal of Advanced Research in Dynamical and Control Systems, 12(2), 130–136. https://doi.org/10.5373/JARDCS/V12I2/S202010015

[13] P. Jyothi, R. B. R. Prakash, P. Srinivasa Varma, Application of Artificial Intelligence to DFIG based Wind Farm for Reactive Power Compensation, International Journal Of Renewable Energy Research, Vol.10, No.2, June, 2020, PP-955-966.

[14] J Rajesh Reddy, A Pandian, R Dhanasekaran, Rami Reddy Ch, B Prasanna Lakshmi, B Neelima Devi (2020), “Islanding detection of integrated distributed generation with advanced controller”, Indonesian Journal of Electrical Engineering and Computer Science, Volume 17, issue no 3,pp. 1626-1631, March 2020, ISSN Number: 2502-4752

[15] M Nikhitha, S Abhishek Kumar, J Sai Srividya, P Sravya, Vinay Are, R B R Prakash, “Mitigation Of Current Harmonics In Wind Power Plant Using Fuzzy Based Shunt APF Controller”, Journal of Critical Reviews, Vol 7, Issue 1, 2020.

[16] Rajesh Reddy, J., Pandian, A.(2019)."Improved ROCOF relay for islanding detection of solar distributed generation", Indonesian Journal of Electrical Engineering and Computer Science, Volume 14, issue no 3,pp. 1105-1113, June 2019, ISSN Number: 2502-4752

[17] Krishna Reddy B, D Seshi Reddy, J Somal, R B R Prakash, "A Novel Control Strategy to manage the Power in hybrid Micro grids", Journal of Advanced Research in Dynamical and Control Systems (2020) Vol 12, No 2, pp 1343-1354. 10.5373/JARDCS/V12I2/S20201172

[18] Mounika Muppavarapu, G G Rajasekhar, T Vijay Muni, R B R Prakash, “Enhancement of Power Quality In A Grid Connected UDE Based PV Inverter”, Journal of Critical Reviews, Vol 7, No 2, 2020 pp 340-343. http://dx.doi.org/10.31838/jcr-07-02-65

[19] R B R Prakash, P Srinivasa Varma, Pandian A, Prasad Rao K, “Model reference adaptive system (MRAS) technique for sensorless scalar control of induction motor”, International Journal of Scientific and Technology Research (2020), Vol 9, No 3, 3193-3198.

[20] Raheema Syed, P. Srinivasa Varma, R. B. R Prakash, Ch. Rami Reddy, “Unit commitment based reliability analysis with contingency constraint”, Indonesian Journal of Electrical Engineering and Computer Science, Vol. 16, No. 1, October 2019, pp. 74-81, DOI: 10.11591/ijeecs.v16.i1.pp74-81