Circulating Current Minimization and load sharing control of the DC Microgrid based on Optimal Droop parameters

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Abstract—The DC microgrids are getting popular as an effective means to integrate various renewable energy sources. The droop control is effectively utilized in order to minimize circulating current among sources of microgrid. The unbalanced cable line impedance is the main cause to enhance circulating current. In this paper, the circulating current among source converter is minimized based on optimal droop parameters. The trade-off between effective load sharing and bus voltage regulation of DC micro grid is mitigated for a range of loading condition of unequal cable line parameters. The optimal droop parameters are calculated based on Grey Wolf Optimization (GWO) technique of the system. The performance analysis of the microgrid is verified by real-time simulator in the dSPACE 1202 platform.

Keywords— Droop control, hysteresis current control, microgrid, Grey wolf optimization.

I. INTRODUCTION

Renewable energy sources like wind, solar, fuel cell etc. connected together due to preserve conventional energy sources and to reduce environmental pollution [1]. Microgrid is a feasible solution to integrate renewable energy sources. Microgrids can be operated either in island and grid-connected modes. Microgrids can be classified into AC and DC microgrids. Due to various applications of DC sources in commercial sectors, telecommunication and data centres, the DC microgrid is nowadays important objective [2,3]. The DC microgrid is somehow simplex in aspects of absence of frequency control and reactive power control [4-6].

The DC bus voltage variation is generated due to abruptly change in input powers and voltage or current feedback error. The circulating current among source converters is raised by the unbalance cable line impedances between the DC bus and source converters [7]. The poor load sharing can rise over stress of any source converter and facilitates maximum power to the load so, the current sharing between the source converter is particularly important [8,9].

The three control structure is consisted by a hierarchical approach as: primary, secondary, and tertiary control. The primary control level consists bus voltage regulation and generally performs based on the droop control method [10-11]. The bus voltage and power flow coordination are regulated by secondary control level. The tertiary control regulates the power flow coordination among microgrids.

The hierarchical control level is also classified based on the communication link as decentralized, centralized and distributed control [8-11]. The decentralized control use the bus voltage reference based on droop control. The source converters can regulate independently. In centralized control, the source converters communicate through central control unit in order to make effective equal load sharing and regulate bus voltage [12]. The centralized control facilitates the flexibility level to achieve aforementioned control objectives. It has a basic problem that is a single point of failure possibility which can reduce the reliability. The distributed control works with only communication link and free from central control units [13-14]. The communication channels are commonly implemented for operating modes. The communication links operate based on the consensus algorithm [15-16]. Therefore, the distributed control provides more reliable and scalable over centralized control.

The distributed control scheme is implemented by average output current signal [9,14] and output voltage signal [12] of source converters. The output current and voltage sharing error are compensated through cascaded proportional integral (PI) controller of the source converter. The operating frequency of the inner and outer loop of cascaded PI controller is different due to inner-loop faster than outer-loop. Therefore, the tuning procedure of cascaded PI parameters is a complex process. In [7,17,18], the dynamic droop resistance are estimated with the help of a droop index algorithm. In [19], the optimal droop parameters are utilized for decentralized control scheme. Therefore, the performance of the distributed control scheme needs to improve in terms of simplex control and for dynamic loading condition.

The distributed control scheme is performed in this paper based on optimal droop parameters (nominal voltage references and droop gain) in order to minimize circulating current within the bus voltage regulation. The droop parameters of the system are optimized by fast convergence GWO algorithm. The optimization problem is considered for various loading conditions. The maximum power on the load side can be achieved by optimizing droop parameters. With the help of real-time simulation, the control objectives of the DC microgrid are successfully validated.

The analysis of the distributed control scheme is described in section II. In section III, the optimization of error problem and GWO algorithm are covered. The real time simulation results are summarized in section IV. In section V, the conclusions are drawn.
II. THE DISTRIBUTED CONTROL SCHEME

A. Droop control

The DC microgrid is considered with two parallel sources due to basic droop control analysis in Fig. 1. The nominal voltage reference and output source current is written as

\[ V_{o,j}^* = V_{o,i} + r_d, i_{o,i} \]  
\[ V_{o,i} = V_o + R_c, i_{o,i} \]  

Therefore, the output current of source converter is summarized as:

\[ i_{o,i} = \frac{V_{o,i}^* - V_o}{(r_{d,i} + R_c)} \]  

where \( i_{o,i}, r_{d,i}, R_c, V_{o,i} \) and \( V_{o,i}^* \) are output current, droop resistance, cable line resistance, output voltage and nominal voltage reference.

The circulating current by two DEU is calculated as:

\[ \Delta i_{12} = \frac{(V_{o,1} - V_o)(r_{d,2} + R_c) - (V_{o,2} - V_o)(r_{d,1} + R_c)}{(r_{d,1} + R_c)(r_{d,2} + R_c)} \]  

where \( \Delta i_{12} \) (circulating current error) may be equal to zero and can be assured by optimal nominal voltage reference and droop gain. The load sharing of two source converter for optimal droop gain and nominal voltage reference is expressed in Fig. 2.

B. The Distributed control method

The DC microgrid consists with three source converters and unequal cable line impedances as shown in Fig. 3. The distributed control scheme of the DC microgrid is shown in Fig. 4. The distributed control is implemented based on voltage droop control. The output voltage is regulated by the hysteresis current control. The source converters are communicated with low bandwidth communication line and it is utilized to make average reference current signal. This current signal from control block diagram can be simplified as

\[ I_{ref,j} = \left[ 1 + \frac{w_{fj} s}{4 k_T} \right] \left[ V_{ref,j} - V_{o,j} \left( \frac{w_{fj}}{s} \right) \right] \]  

where \( w_{fj} \) is used to mitigate high frequency ripples of output voltage.

The average reference current signal of the DC microgrid is calculated as

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**Fig. 1.** Simplified with two source model of DC microgrid

**Fig. 2.** Droop characteristic of two source model of microgrid

**Fig. 3.** Simulated the DC microgrid block diagram

**Fig. 4.** The distributed control block diagram
Therefore, the average reference current signal with communication delay for three system is given as

$$I_{ref} = \frac{\sum_i I_{ref,i}}{n}$$  \hspace{1cm} (6)$$

The average reference current signal with communication delay by the $i^{th}$ source converter is

$$I_{ref,i} = \frac{I_{ref,1} + I_{ref,2}G_{d,2} + I_{ref,3}G_{d,3}}{3}$$  \hspace{1cm} (7)$$

and communication delay by the $i^{th}$ source converter is

$$G_{d,i} = \left( \frac{1}{1+T_{d,i}} \right)$$  \hspace{1cm} (8)$$

Therefore, the average reference current signal with communication time delay of the converter is finalized as

$$\tilde{I}_{ref,i}(s) = \frac{V_{ref,i}}{V_{n}/T_{a,i}} \left( 1 + \frac{w_{ref,i}}{4sT_{a,i}} \right) \left( \frac{1+G_{d,2}+G_{d,3}}{3} \right) \times \left[ V_{ref,i} - \left( \frac{w_{ref,i}}{s + w_{ref,i}} \right) V_{ref} \right]$$  \hspace{1cm} (9)$$

III. OPTIMAL DROOP PARAMETERS BASED ON GWO

The droop parameters need to optimize in order to minimize circulating current and bus voltage regulation. The optimization problem can be developed for the optimal droop parameters. In [9,19], the aforesaid control objectives of the system can be achieved by minimizing voltage drop and current sharing error [9]

$$e_v = \sqrt{\sum_{i=1}^{N} \left( \frac{\frac{v_{max}}{v_{min}}}{I_{a,i}} - \frac{I_{a,i}}{I_{a,i}} \right)^2}$$  \hspace{1cm} (10)$$

$$e_r = V_o - \sum_{i=1}^{N} \frac{V_{ref,i}}{N}$$  \hspace{1cm} (11)$$

The total error in the system is described as

$$e_{t} = w_{e}e_v + w_{r}e_r$$  \hspace{1cm} (12)$$

The fluctuation in output current is found faster than the bus voltage variation. Therefore, the current weight factor $w_c$ is consider more value than the voltage weight factor $w_v$.

The specific constraints of micro grid are summarized as:

$$\begin{align*}
I_{ref,i}^{min} & \leq I_{ref,i} \leq I_{ref,i}^{max} \\
V_{ref,i}^{min} & \leq V_{ref,i} \leq V_{ref,i}^{max} \\
e_{t} & = w_{e}e_v + w_{r}e_r
\end{align*}$$  \hspace{1cm} (13)$$

If there is constraint violate the constant value $e_{c}$ is added in (13).

The optimization tools such as the grey wolf and particle swarm can be implemented for the satisfactory solutions [20]. The grey wolf optimization has advantages over these heuristic optimization techniques such as it is easy to implement in terms of simple structure, convergence and less storage requirement than the other techniques [21,22]. The flow chart of the GWO algorithm is expressed in Fig. 5 (a).

The droop parameters of the DC microgrid are random particles of GWO algorithm. The range of droop gains and nominal voltage references are defined in Table I. The number of particles in each dimension is responsible to minimize the total error which is calculated after load flow analysis (simulation). The DC microgrid parameters are summarized as system parameters in Table II. The number of particles and iterations are considered 50 each for GWO algorithm. In Fig. 5 (b), the total error values are computed for alliteration. At the end of the final iteration, optimized alpha particle for each dimension are considered for optimum droop resistances and voltage references which are summarized in Table III

![Fig. 5. (a) The flow chart of global alpha particle and (b) total minimum fitness error trajectory](image-url)

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<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min and Max Nominal Voltage references</td>
<td>$V_{ref}$</td>
<td>570, 630</td>
<td>V</td>
</tr>
<tr>
<td>Min and Max Droop resistances</td>
<td>$R_{d}$</td>
<td>0.2</td>
<td>Ω</td>
</tr>
<tr>
<td>Current weight factor</td>
<td>$w_{c}$</td>
<td>0.9</td>
<td>-</td>
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</table>

TABLE I. GWO PARAMETERS
TABLE II. SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus voltage</td>
<td>$V_o$</td>
<td>600</td>
<td>V</td>
</tr>
<tr>
<td>Source Converter inductance and capacitance</td>
<td>$L,C$</td>
<td>10e-3, 44e-3</td>
<td>H,F</td>
</tr>
<tr>
<td>Operating frequency of LPF</td>
<td>$w_{lpf}$</td>
<td>100π</td>
<td>rad/s</td>
</tr>
<tr>
<td>Communication time delay</td>
<td>$T_d$</td>
<td>5</td>
<td>ms</td>
</tr>
<tr>
<td>Hysteretic current band</td>
<td>$\Delta I$</td>
<td>0.5</td>
<td>A</td>
</tr>
<tr>
<td>Input voltage of source</td>
<td>$V_{si}$</td>
<td>200</td>
<td>V</td>
</tr>
<tr>
<td>Line impedances #1,2,3</td>
<td>$[Z_{c,1}, Z_{c,2}, Z_{c,3}]$</td>
<td>$[2+50e-3i, 3+50e-3i, 4+50e-3i]$</td>
<td>Ω</td>
</tr>
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</table>

TABLE III. ALPHA PARTICLE OF GWO

<table>
<thead>
<tr>
<th>Optimal droop parameters</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[r_{d1}, r_{d2}, r_{d3}]$</td>
<td>[1.5122, 1.5588, 1.4982]</td>
<td>Ω</td>
</tr>
<tr>
<td>$[V_{ref,1}, V_{ref,2}, V_{ref,3}]$</td>
<td>[628.5824, 626.3382, 629.9854]</td>
<td>V</td>
</tr>
</tbody>
</table>

IV. REAL-TIME SIMULATION RESULTS

In order to minimize circulating current as well as bus voltage regulation of the DC micro grid, the system performance are observed based on optimal droop parameters. The communication time delay of the source converter is considered 5 ms for all the source models.

The DC microgrid performance is observed by conventional droop controller and proposed distributed controller with low ($R_{load} = 75 \, \Omega$), medium ($R_{load} = 24 \, \Omega$) and full ($R_{load} = 12 \, \Omega$) loading conditions. In Fig. 6, the load sharing is validated by real-time simulator. The load sharing is achieved by conventional droop control in starting and after 80 s, it performs based on the distributed control scheme. The circulating current value by the conventional droop controller are 1.06, 4.43 and 9.8 A with low, medium and full loading conditions respectively. Whereas, the circulating current by the distributed control scheme are 0.002, 0.21 and 0.85 A respectively.

The reference DC bus voltage is considered 600 V. In Fig. 7, the bus voltage regulations by a conventional droop control are $+20.3, +4.6,$ and $-17$ V with low, medium and full loading condition respectively, whereas $+20, +3,$ and $-20$ V by the distributed control scheme. The output voltages of distributed energy units are unequal due to unbalanced voltage drop across the cable lines. Therefore, the bus voltage deviation with loading conditions is maintained within the permissible limits.
range. The quantitative observation of exact values of output current and voltage is given in Table IV.

### Table IV. Quantify Results

<table>
<thead>
<tr>
<th>Decentralized Distributed</th>
<th>Load current of source converter</th>
<th>Max current sharing error (A)</th>
<th>Bus Volt. (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#DEC #DIS</td>
<td>#1 #2 #3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Low loading condition (R_{load}=75\ \Omega)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEC</td>
<td>3.5</td>
<td>2.78</td>
<td>2.44</td>
</tr>
<tr>
<td>DIS</td>
<td>2.762</td>
<td>2.76</td>
<td>2.758</td>
</tr>
<tr>
<td><strong>Medium loading condition (R_{load}=24\ \Omega)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEC</td>
<td>10.9</td>
<td>8.0</td>
<td>6.47</td>
</tr>
<tr>
<td>DIS</td>
<td>8.5</td>
<td>8.4</td>
<td>8.29</td>
</tr>
<tr>
<td><strong>Full loading condition (R_{load}=12\ \Omega)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEC</td>
<td>21.6</td>
<td>15.2</td>
<td>11.8</td>
</tr>
<tr>
<td>DIS</td>
<td>16.6</td>
<td>16.2</td>
<td>15.75</td>
</tr>
</tbody>
</table>

### V. Conclusion

The performance of the DC system is observed with the optimal droop parameters. The circulating current is suppressed with the help of optimal nominal voltage reference by GWO algorithm. The bus voltage deviation for unequal and large value of cable line impedances is maintained within the permissible limits. The transient response of the distributed control of the system is performed in the specific range. The real-time simulation results are observed in dSPACE 1202 platform. Further, the distributed controller may be utilized in the DC microgrid clusters.

### References


