Fault Detection and Isolation in DC Microgrid using Least Square Method

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Abstract—DC Microgrid protection is essential for continuous power supply to the customers. The objective of this proposed work is to detect and locate the fault for fast restoration of the system to normal operation. The proposed protection scheme for DC Microgrid uses Intelligent Electronic Device for detecting and locating the fault. For accurate fault location, the Least Square based estimation technique is used to estimate the inductance of the fault path, from which the direction of fault will be identified. Using the direction of the fault information, internal and external faults are discriminated. The proposed system is tested with various fault conditions and locations in DC Ring Microgrid. The DC Microgrid with ring configuration and its protection schemes are simulated using MATLAB/Simulink environment.

Index Terms—DC Ring Microgrid, Least Square Estimation Method, IED’s.

I. INTRODUCTION

The electrical power system is significantly changing in order to cope with the increasing participation of various distributed energy resources. The arising concerns on environmental and sustainable energy issues like greenhouse gas emission, depletion on energy sources, ageing of current transmission and distribution infrastructure and ever-growing demand of electrical energy due to conventional energy sources have promoted the development of distributed renewable power generation [1]. These changes are required to ensure reliable and clean energy sources and to improve the quality of life. Since renewable power sources are naturally dispersed, it is very difficult for the power system to manage the growing and intermittent distributed power generation in a traditional way. In order to effectively manage distributed generation sources, load and energy storages, all the distributed units are integrated together to form a micro power system at the distribution side, the Microgrid.

Microgrid is a low or medium voltage electrical network consisting of especially renewable sources of energy, energy storage devices and loads. The electrical network can be AC, DC or combination of both. It is operated either in a grid-connected mode or an islanded mode [2]. Microgrids are normally interconnected to the distribution networks via a direct connection or an interfacing power converter, which gives an opportunity to get power from the utility grid and also feeds power back to utility grid during surplus power generation. In the event of a fault, the microgrid disconnects from the utility network as fast as possible and controls its load using different control methods [3]. In this condition, the microgrid operates in an islanding mode. The concept of microgrid is an advancement towards present unidirectional (i.e. generation → transmission → distribution) electrical distributed networks to futuristic bidirectional active networks (i.e. generation → transmission → distribution ↔ distributed generations), aimed to meet the growing energy demand. The possibility of securing power from renewable energy based Distributed Generation (DG) is the key ingredient to the Microgrid.

II. DC MICROGRID RING CONFIGURATION

A protection scheme for smart DC microgrid with ring configuration is proposed. Using local Intelligent Electronic device (IED), voltage and current data during fault, a LS based technique estimates the inductance of the fault path which is able to discriminate forward and reverse faults with respect to the IED [4]. This fault direction information is communicated to the other end IED of a line segment. Using the local and other end fault direction information, each IED identifies any internal fault of the line segment correctly. Signals generally being contaminated by noise in a system, as proposed method uses least square filtering, it is able to estimate the scene inductance in IEDs accurately. A smart DC microgrid with ring configuration is considered as shown in Fig. 1.
To the microgrid PV array is connected which supply power to different DC and AC loads. For efficient and reliable energy management and as a backup, battery is connected to the microgrid [28]. Using bidirectional AC-DC front-end converter and DC-DC converters, integration of sources, loads and storage is done. Grid forming DGs regulate voltage and behave as a slack terminal in the islanded DC microgrid. PV array operate as grid following sources that injects power under maximum power point tracking (MPPT) mode. Hierarchical droop control strategy [5] for grid forming DGs is considered. Inner current and outer voltage controllers including MPPT in the DC-DC converters for grid following sources are modelled [6]. Line segments in the DC ring consist of cables of different lengths [7]. One of the main limitations of present day converters is that their fault current withstand is much lower than that of thyristor-based converters, typically twice the nominal current rating of the converter [8].

The proposed protection scheme for the DC Microgrid uses the measured voltage and current data’s from the system. During the fault, the disturbance index $h$ is checked, if it exceeds the threshold, the fault is detected and the location of fault is carried out. The voltage, current and its derivatives are sampled and using least square method estimation of seen inductance at IED is obtained. If the inductance seen by the IED is negative at one end of the line segment and if the other end IED also sees negative inductance, then the fault is consisted to be the forward fault and tripping command is given to the corresponding circuit breaker [9]. If any one of the IED shows seen inductance positive, then it is a reverse fault and the tripping is not derived.

A. Fault Detection
Fault detection is an important part of DC Microgrid protection. Rapid fault detecting strategy is a prerequisite for the DC protection scheme. It aims to detect if there is a fault, discriminate which is the faulty part, determine which breakers to trip and send them such signals. This is realized by the protection relays. The fault detection function is designed to overcome the problem of limited fault current magnitude. To detect the disturbance such as fault, the disturbance index ($h$) is calculated by

$$h = \frac{1}{N\Delta t} \sum_{j=1}^{N} (|i_{j+1} - i_j|)$$ ......(3.1)

where
- $i_j$: Sample value of current
- $\Delta t$: Sampling interval
- $N\Delta t$: Change in current over a period
- $i_{j+1}$ is the current value that is sampled and $\Delta t$ is the sampling interval. The change in current over a period of time $N\Delta t$ is 5A. For 4kHz sampling, the threshold value is fixed as 4000A/s. When the disturbance index $h$ exceeds the threshold $\xi$, the fault is detected and the algorithm triggers the main algorithm to accurately identify the fault location to derive the protection decision to restore to normal operation.

B. Fault Location
Fault locating is to estimate the exact fault location in the faulty line. Although this is not compulsary in the protecting...
scheme, fault locating is still significant and essential in DC cable short circuit since these faults are almost always permanent and require repairs later on [10-12]. In this circumstance, it is usually assumed that the faulty line has already been determined and isolated from the system. As a result, speed is no longer the highest priority in this condition, and that the data is usually processed offline. However, it is always desirable that the fault location can be estimated only with the data which have already been obtained during the fault.

C. Least square based estimation technique

Under normal condition, there is no inductance in the DC system. During transient condition in DC system, the inductance occurs and the drop in the line increases due to effect of inductance at that period. From the figure 5.2, the voltage, \( v_C \) at any time \( t \) will be

\[
\begin{align*}
v_C &= v_D + i_{C.1} R_{CD} + L_{CD} \frac{di_{C.1}}{dt} \quad \text{... (3.2)}
\end{align*}
\]

where \( v_C, i_{C.1} \) are the voltage and current seen by \( IED_{C.1} \) during transient and \( R_{CD}, L_{CD} \) are the resistance and inductance of cable section CD. During steady state voltage at bus C, \( V_C \) will be

\[
\begin{align*}
V_C &= V_D + i_{C.1} R_{CD} \quad \text{... (3.3)}
\end{align*}
\]

where \( V_C, i_{C.1} \) are the RMS voltage and current seen by \( IED_{C.1} \). The prefault voltage and current values are constant for an event.

i) Forward fault

In the DC ring microgrid, line sections BC and CD and a ground fault is created at instant \( t_1 \) in the line section CD and the voltage and current at \( IED_{C.1} \) is analyzed. Voltage at bus C will be

\[
\begin{align*}
v_{CF}(t_1) = v_f(t_1) + i_{C.1f}(t_1) R_{CF} + L_{CF} \frac{dif_{C.1}}{dt} \quad \text{... (3.4)}
\end{align*}
\]

where \( v_{CF}(t_1) \) and \( i_{C.1f}(t_1) \) are the sample voltage and current seen \( IED_{C.1} \) by during fault. \( v_f(t_1) \) is the voltages at fault point and \( R_{CF}, L_{CF} \) are the resistance and inductance from \( IED_{C.1} \) to fault point.

Subtracting (3.4) which is the prefault voltage, from (3.3),

\[
\begin{align*}
v_{CF}(t_1) - V_C &= v_f(t_1) - V_D + i_{C.1f}(t_1) R_{CF} - i_{C.1} R_{CD} + L_{CF} \frac{dif_{C.1}}{dt} \\
\Delta v_C &= v_f(t_1) - V_D + i_{C.1f}(t_1) R_{CF} - i_{C.1} R_{CD} + L_{CF} \frac{dif_{C.1}}{dt} \quad \text{... (3.5)}
\end{align*}
\]

\( \Delta v_C = \frac{dv_C}{dt} \) is the voltage error difference of \( IED_{C.1} \) and \( IED_{C.2} \) at time \( t \).

\[
\begin{align*}
\Delta v_C &= v_f(t_2) - V_D + i_{C.1f}(t_2) R_{CF} - i_{C.1} R_{CD} + L_{CF} \frac{dif_{C.1}}{dt} \quad \text{... (3.6)}
\end{align*}
\]

Subtracting (3.6) from (3.5),

\[
\begin{align*}
\Delta v_C &= v_f(t_2) - v_f(t_1) + i_{C.1f}(t_1) R_{CF} - i_{C.1f}(t_2) R_{CF} - i_{C.1} R_{CD} + L_{CF} \frac{dif_{C.1}}{dt} \\
\Delta v_C &= v_f(t_2) - v_f(t_1) + i_{C.1f}(t_1) R_{CF} - i_{C.1f}(t_2) R_{CF} - i_{C.1} R_{CD} + L_{CF} \frac{dif_{C.1}}{dt} \quad \text{... (3.7)}
\end{align*}
\]

For the two sides of fault situations in the system, \( IED_{C.1} \) measures the current \( i_{C.1} \) and voltage \( v_C \). From equation (3.5) and (3.7), it is to be observed that for forward and reverse fault \( i_{C.1} \) is \( i_{C.1f}(t_1) \) and \( i_{C.1f}(t_2) \) respectively. Similarly, the rate of change of current seen by \( IED_{C.1} \) during fault situation is

\[
\frac{dif_{C.1}}{dt} \bigg|_{t_1} \text{ and } \frac{dif_{C.1}}{dt} \bigg|_{t_2}
\]

in case of forward and reverse direction respectively.

Using Least Square technique, equations (3.5) and (3.7) can be written as

\[
[A][x] = [m]
\]

where \( [A]^+ = ([A]^T [A])^{-1} \) which is the left pseudo-inverse of \([A]\)

The parameters seen by the IEDs are obtained from the computation of (3.8). For forward fault the voltage and current relation in (3.5) and corresponding relation for reverse fault in (3.7) reveals that the coefficient of \( i_{C.1} \) are \( L_{CF} \) and \( L_{CD} \) respectively. Therefore, when this coefficient which is termed as seen inductance is estimated for any case using (3.8), a negative value for forward fault and a positive value for reverse fault are obtained. This principle using estimated inductance is successfully applied for identifying direction of fault in DC Microgrid.

IV. RESULT AND DISCUSSION

The DC Microgrid with ring configuration is simulated in the MATLAB R2014a /Simulink environment. The DC Microgrid is constructed with 6 buses connected through DC cables. Fig 4.1 Simulation model for the proposed DC Microgrid with IED’s.

There are 6-line segments connecting the buses, each containing 2 IEDs at both the ends of the line. There are totally 12 IEDs associated with corresponding solid-state circuit breaker.

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There are 2 solar panels having 500kW and 125kW capacity with temperature and irradiance at standard test condition. Maximum Power Point Tracker (MPPT) controller is used to maximize the amount of power produced from the array. Lead acid battery is used as a backup storage. DC to DC boost converter are used increase the input voltage. DC loads of 200kW, 200kW, 100kW are used. Solar, battery and loads are incorporated into the DC microgrid by specifying the DC output at 350V DC.

Fig 4.2 Simulation model of solar with DC-DC Converter

Fig 4.2 shows the solar source of 500kW capacity with standard temperature of 25°C and irradiance of 1000W/m² is used in the DC Microgrid.

Fig 4.3 output voltage waveform of 500KW solar panel

Fig 4.4 output current waveform of 500KW solar panel

Fig 4.5 Simulation model of battery with DC-DC Converter

Fig 4.5 shows the simulation model of DC-DC converter. Battery regulates DC voltage by maintaining the microgrid power balance through their ability to supply the power deficit or absorb extra power. Lead-acid batteries are commonly used for PV-based renewable systems. The lead-acid type battery with 90V and 400 Ah rated capacity.

Fig 4.6 output voltage waveform of battery

Fig 4.7 current voltage waveform of battery

Fig 4.8 Simulation model of the proposed IED associated with solid – state circuit breaker

IED is simulated in the MATLAB function-coding block to detect and locate the fault. The IED acquire voltage and current data after sampling. The voltage and current values are sampled at 4kHz sampling rate.
The solid-state circuit breaker is designed using two thyristors in anti-parallel because the switch requires a continuous current carrying and a short time overcurrent rating equal to the feeder faults level. It has low conduction losses. The thyristors in the feeder are normally energized by continuous and synchronized firing control signal. On detection of fault, these firing pulses are stopped to break the current. The SSCB block is controlled by signals from firing controller.

Fig 4.10 shows the firing controller for SSCB is designed to generate firing signals to turn on the thyristors, a saw-tooth signal with a DC reference signal are compared. The resultant pulse signal is used in the SSCB block. The controlling signal strongly depends on the level of a sensed quantity that is usually either current or voltage. The firing command decides the SSCB status whether to turn-on or turn-off for interrupting the fault current.

Table 4.1 System data for the proposed DC Microgrid

<table>
<thead>
<tr>
<th>System Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Voltage</td>
<td>350V DC</td>
</tr>
<tr>
<td>Base Power</td>
<td>500 kW</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>$V_{mp} = 54.7V, I_{mp}=5.58A$ at STC</td>
</tr>
<tr>
<td>PV Array 1 Rating</td>
<td>125 kW</td>
</tr>
<tr>
<td>PV Array 2 Rating</td>
<td>500kW</td>
</tr>
<tr>
<td>Battery</td>
<td>96 V, 0.4 kAh</td>
</tr>
<tr>
<td>Load</td>
<td>500kW</td>
</tr>
</tbody>
</table>

V CONCLUSION

The fault detection and location for the DC Microgrid system is simulated using MATLAB/Simulink platform. The proposed protection scheme estimates the fault inductance at each IED during the fault and discriminates the forward and reverse faults. The results show the credibility for achieving fault detection and location with line to ground fault in different fault locations with a good level of selectivity. The performance of the proposed method is better for high resistance fault compared to current based directional protection.

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REFERENCES


