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Firefly algorithm optimized robust protection scheme for DC microgrid

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Various topologies of Direct Current (DC) microgrid have been proposed in the literature by considering practical requirements. One of the important criteria in topology selection is the availability of a well functioning protection scheme. A significant part of the DC microgrid protection system literature considers differential protection schemes for various topologies. However this scheme doesn't work satisfactorily with noisy measurements. Noisy measurements are a reality and can not be avoided for any real engineering system. This article proposes a robust protection scheme to alleviate some problems associated with topology selection. The proposed scheme considers noisy current measurements and works by estimating time derivative of line currents. The proposed approach uses continuous finite-time convergent differentiator to estimate the derivative. The gains of the differentiator were tuned through Firefly algorithm based optimization technique. Matlab/Simulink (®) based simulations verified the effectiveness of the proposed approach over the existing differential current scheme.

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1 Introduction

The rapid expansion of renewable energy sources brought a lot of opportunities along with various operational challenges [1-3]. One of the benefits that came with renewable energy is the rapid growth in the number of operational microgrid. Out of the three main choice of network types of microgrid *i.e.* AC, DC and mixed, recently the DC microgrid started to become popular [4]. The popularity of DC microgrid came from various advantages of DC distribution system. For example, lower loss than AC, easy parallelization, high power transfer capacity etc. All of these benefits made DC microgrid a very popular choice.

Driven by practical requirements of specific DC microgrid applications, a number of hardware topologies have been proposed [5-7]. For safe and reliable operation of DC microgrid, a well-functioning protection system is instrumental in any topology. Its principal objective is to minimize the propagation of disturbances by detecting and isolating faults within the minimum time frame. Protection of DC systems is in general a challenging task due to difficulties in extinguishing arc, which on the contrary happens naturally in AC systems. Accurate short-circuit current calculation and fault-detection are the most important prerequisites for good design of protection system [8].

A major operational challenge in the adoption of DC microgrid is the scarcity of appropriate and competent fault protection solutions. Protection system includes protective devices such as fuses, circuit breakers, load break switches, and relays etc. Frequently DC microgrids have Voltage Source Converters (VSC), which require very rapid protection and isolation from the network where the fault occurred. Due to the inherent nature of the DC distribution system (large DC capacitor, low

impedance DC cable etc.), high transient currents and voltages may appear from a fault in the system. That is why high fidelity protection scheme is required at a reasonable cost to be commercially viable.

The existing literature on the protection scheme for DC microgrid is not very old and rich like its AC counterpart. In AC network, various methods exist to detect and isolate faults [9–11]. However, some of the fault detection and isolation methods depend on the spectral analysis of fault signatures like line current [12–14]. However, the same analysis can't be done for the case of DC because it doesn't have any spectral property. As a result, various alternative solutions have been proposed in the literature [15–19].

In [20], a protection mechanism for VSC-Multi Terminal DC (MTDC) grid has been proposed by opening all the ac-side circuit breakers (AC-CB) of the VSC's in the case of fault in any one of the line. However, opening all the AC-CB's in the case of fault in any line is not an ideal situation. To overcome the limitations of [20], another method was suggested in [18] where complete shutdown is not necessary. The method of [18] works through calculating the difference of currents. In the same line of research, recently in [17] a similar approach has been taken to detect fault in DC microgrid. In [17], the difference between the currents in both sides of a protected feeder/zone is continuously measured. If the absolute value of this differential current is found to be greater than a threshold, a trip signal is sent to the corresponding DCCB in each ends of the line. For various other works that use current difference as fault signature, readers can consult [19, 21]

A significant part of the existing literature depends heavily on differential protection scheme. In fact, since the fault current level, the rate-of-change of the current, status of DGs, and fault resistance have relatively low impact on the perfor-

mance of differential protection, they are the best options for the protection of DC systems embedding DGs [16]. However, the differential protection schemes mentioned before don't consider any measurement noise explicitly. Measurement noise may introduce false alarm in the protection scheme. Power converter switching is a source of noise in DC power system. Moreover, Analog to Digital Conversion (ADC) also introduces noise in the measurement.

In the context of noisy measurement, estimation of the actual signal or the time derivative has a very rich literature. A popular way is to use low-pass filtering to cut-out the high frequency measurement noise. However, filtering introduces delay. An intelligent way to overcome this problem is to use real-time techniques. For example, recently in [22], a continuous finite-time convergent differentiator for real-time differentiation has been proposed based on a strong Lyapunov function. In this work, the differentiator proposed in [22] will be applied to improve the results of existing differential protection scheme by considering noisy measurements. Finding the optimal gains of the differentiator is very crucial for the effective operation of the proposed protection scheme. Modern evolutionary optimization techniques can be very useful in this regard.

Biologically inspired evolutionary optimization algorithms such as genetic algorithms (GAs), ant colony systems (ACS), artificial immune systems (AIS), particle swarm optimization (PSO) techniques, etc., have been extensively used for various engineering applications [23–26]. They have also been used in the case of differentiator design [27]. The optimization algorithm selected for tuning the gains of URED should ideally possess the properties of simple computational steps, faster convergence, and guaranteed convergence together with the feasibility of implementation in a low-cost digital micro-controller that normally comes with digital relay.

Recently, Yang has developed a meta-heuristic algorithm known as firefly algorithm (FA) and is available in [28]. This algorithm is inspired by the flashing behavior of fireflies to attract other fireflies for mating purpose. Recent works [29,30] confirmed the superiority of FA in solving complex optimization problems.

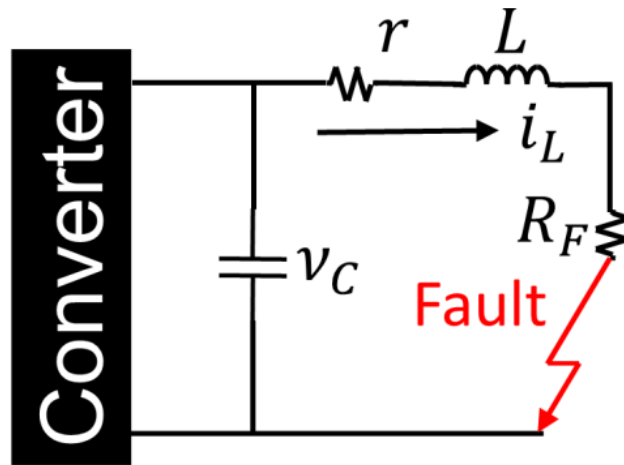
So, the main objective of this article is to alleviate the challenges associated with the adoption of various microgrid topologies. One of the solution to the challenges is a robust protection system for DC microgrid. That is why the main objective will be attained by improving the line current difference based method by real-time filtering of noisy measurements through continuous finite-time convergent differentiator. The gains of the sliding mode differentiator were optimized through Firefly algorithm.

The rest of the article is organized as follows: System analysis during fault can be consulted from Section 2. Proposed protection scheme including differentiation of the noisy signal and the tuning of the gains of the differentiator can be found in Section 3. System configuration and simulation results and discussions is given in Section 4. Finally, Section 5 concludes this work.

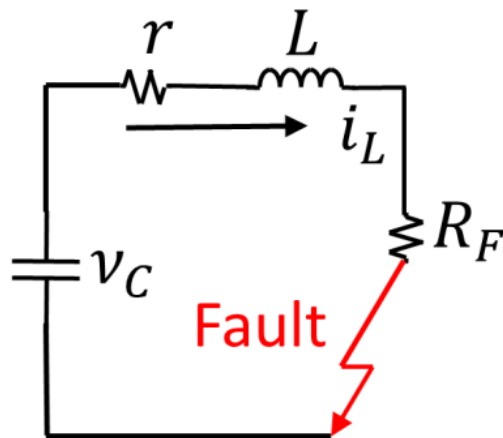
2 Analysis during fault

Analytical expression of the fault on DC bus has been studied in following the ideas presented in [21]. In a general case, let us consider a small section of the DC network during low impedance fault. In this case, the faulted network section and its equivalent circuit is shown in Fig. 1 . The current response of the equivalent RLC circuit can be expressed as:

$$i(s) = \frac{\nu_C(0)/L + i_L(0)s}{s^2 + \frac{R}{L}s + \frac{1}{LC}} \quad (1)$$



(a)



(b)

Figure 1. (a) Faulted network section and (b) its RLC equivalent circuit.

where, $i_L(0)$ is the current through the inductor and $\nu_C(0)$ is the voltage across the capacitor, just before occurring the fault. From eq. (1), in time domain, di/dt can be determined as:

$$\begin{aligned} \frac{di}{dt} = & \frac{\nu_c(0)}{L(p_2 - p_1)} [-p_1 e^{-p_1 t} + p_2 e^{-p_2 t}] \\ & + \frac{i_L(0)}{p_2 - p_1} [p_1^2 e^{-p_1 t} - p_2^2 e^{-p_2 t}] \end{aligned} \quad (2)$$

where, p_1 and p_2 are the poles of the eq. (1). Immediately, after the fault at $t = 0$, eq. (2) become,

$$\left| \frac{di}{dt} \right| = \frac{\nu_c(0)}{L} - i_L(0)(p_1 + p_2) \quad (3)$$

The second term of eq. (3) can be neglected. As a result, eq. (3) reduces to:

$$\left| \frac{di}{dt} \right| = \frac{\nu_c(0)}{L} \quad (4)$$

As L changes with the length of line considered, the magnitude of $\frac{di}{dt}$, found by using (4) depends on the location of the fault. This characteristics of di/dt during fault can be utilized to design the protection system. Since, the computation and control in power system is generally done in discrete-time, then eq. (4) can be written as:

$$\frac{\Delta i}{\Delta t} = \frac{\nu_c(0)}{L} \quad (5)$$

where, $\Delta i = i_k - i_{k-1}$, $\Delta t = t_k - t_{k-1}$, k is the current sampling time and $k - 1$ is the immediate previous sampling time. The estimation of $\frac{\Delta i}{\Delta t}$ will be done through the FA optimized continuous finite-time convergent differentiator (Section 3).

3 Proposed protection scheme

The proposed protection scheme works through estimating $\frac{\Delta i}{\Delta t}$ in the context of noisy measurements of line current. As mentioned in the Introduction, real-time differentiation of noisy signals has a rich literature. Out of various choices, for this work continuous finite-time-convergent differentiator proposed in [22] has been selected. A short description of this differentiation technique is given below:

3.1 Continuous finite-time-convergent differentiator

Let the input signal $f(t)$ to the differentiator be a Lebesgue-measurable function defined on $[0, \infty)$, and $f(t) = f_0(t) + \nu(t)$. The first term $f_0(t)$ is a twice differentiable unknown base signal, with second derivative bounded by a constant smaller than $L_2 > 0$. The second term $\nu(t)$ represents a bounded noise signal with $|\nu(t)| \leq \mu$, where $\mu > 0$ represents the bound of the noise amplitude. The discrete measurement of the input signal $f_0(t)$ can be also interpreted as noise affecting it. With $\varsigma_1 = f_0(t)$, $\varsigma_2 = \dot{f}_0(t)$ a model of the input base signal is given by

$$\dot{\varsigma}_1 = \varsigma_2, \dot{\varsigma}_2 = \ddot{f}_0 \quad (6)$$

To differentiate the unknown base signal, consider the auxiliary equation $\dot{x}_1 = z_1$, where z_1 is the output of the differentiator. Then the main aim is to construct a continuous finite-time-convergent differentiator with prescribed convergence time bounded by a constant and give a robust estimation of $\dot{f}_0(t)$ using only the measurement of $f_0(t)$. Let $\sigma_1 = z_1 - \varsigma_1$ be the estimation error between the base signal and the integral of the differentiator output. Then, the following continuous differ-

entiator can be proposed:

$$\dot{z}_1 = z_2 - k_1 |\sigma_1|^{\frac{\alpha+1}{2}} \text{sgn}(\sigma_1) \quad (7)$$

$$\dot{z}_2 = -k_2 |\sigma_1|^\alpha \text{sgn}(\sigma_1)$$

where, $0 < \alpha < 1$ is a scalar, k_1 and k_2 are positive gains to be designed. If $|\ddot{f}_0(t)| \leq L_2$, with $L_2 > 0$ a known positive constant along with $0 < \alpha < 1$, then (7) is finite-time-convergent if the gains k_1, k_2 are chosen as below:

$$k_1 > 0 \quad (8)$$

$$k_2 > \frac{2(k_1^2 + 4)L_2^2}{k_1^2(\alpha + 1)}$$

Equation (7) provides exact estimation of the derivative in the noise free case. In the presence of bounded noise $|\nu(t)| \leq \mu$, the differentiation error vector $\sigma(t) = [\sigma_1(t) \ \sigma_2(t)]^T$ will be bounded. The differentiation error will depend on the amplitude of the noise.

Since, the data collections and calculations in power systems are usually done in discrete-domain, eq. (7) was discretized using Euler method and can be written as:

$$\begin{aligned} z_1(k+1) &= z_1(k) + \\ & T_s \left\{ z_2(k) - k_1 |\sigma_1(k)|^{\frac{\alpha+1}{2}} \text{sgn}(\sigma_1(k)) \right\} \\ z_2(k+1) &= z_2(k) - T_s k_2 \{ |\sigma_1(k)|^\alpha \text{sgn}(\sigma_1(k)) \} \end{aligned} \quad (9)$$

The gains of the differentiator can be designed using (8). However, eq. (8) gives the range of the gains not the exact values. In that case, the exact gains can be found through the help of optimization algorithms from the suggested values of k_1

and k_2 . In this work, evolutionary optimization algorithm will be considered. Firefly Algorithm (FA) [31] has been selected to tune the gains.

3.2 Firefly algorithm (FA)

FA algorithm recently became very popular due to its superior performance over existing methods. FA is a nature-inspired meta heuristic algorithm initially proposed by X-H Yang in 2007 [28]. FA has many similarities with popular meta heuristics algorithms like Particle Swarm Optimization (PSO). FA was based on the idealized flashing patterns and behavior of fireflies.

In [28], the following three rules were considered regarding the idealized flashing characteristics of firefly:

- all fireflies are unisex *i.e.* attractiveness is gender independent;
- Attractiveness is proportional to their brightness and both of them depend on distance. A less bright nearby firefly is more attractive than a bright firefly located faraway. However, firefly moves randomly in case no other firefly is particularly attractive.
- The landscape of the objective function of the optimization problem affect or determine the brightness *i.e.* light intensity of a firefly.

The variation of light intensity and the formulation of the attractiveness are two very important issues for FA based optimization. For the sake of simplicity, it can always be assumed that the attractiveness of a firefly is determined by its brightness or light intensity which in turn is associated with the encoded objective function. Let us consider that the brightness I of a firefly at a particular location \mathbf{x} can be chosen as $I(\mathbf{x}) \propto f(\mathbf{x})$. However, the attractiveness β is relative, it should be seen

in the eyes of the beholder or judged by the other fireflies. Thus, it should vary with the distance r_{ij} between firefly i and firefly j . As light intensity decreases with the distance from its source, and light is also absorbed in the media, so we should allow the attractiveness to vary with the degree of absorption. In the simplest form, the light intensity $I(r)$ varies with the distance r monotonically and exponentially. That is,

$$I = I_0 e^{-\gamma r}, \quad (10)$$

where, I_0 is the original light intensity and γ is the light absorption coefficient. As a firefly's attractiveness is proportional to the light intensity seen by adjacent fireflies, the attractiveness β of a firefly can be defined by,

$$\beta = \beta_0 e^{-\gamma r^2} \quad (11)$$

where β_0 is the attractiveness at $r = 0$. It is to be noted here that γr^2 can be replaced by any γr^m with $m > 0$. Next, let us consider the Euclidean norm $r_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\|$ between two fireflies i and j located at \mathbf{x}_i and \mathbf{x}_j respectively. Then, the movement of a firefly i that is attracted by a brighter firefly j can be written as,

$$\mathbf{x}_i^{t+1} = \mathbf{x}_i^t + \beta_0 e^{-\gamma r_{ij}^2} (\mathbf{x}_j^t - \mathbf{x}_i^t) + \alpha \epsilon_i^t, \quad (12)$$

In eq. (12), the second term appears from the attraction and the third term is coming from randomization with the vector of random variables ϵ_i being drawn from a Gaussian distribution. In eq. (12), a very important parameter is the light absorption coefficient γ . It plays a crucial role to determine the variation of attractiveness and at the same time the convergence speed of the algorithm along with the behavior of the algorithm [28].

In theory, γ is in the interval $[0, \infty)$. When, $\gamma = 0$, then $\beta = \beta_0$ *i.e.* the attractiveness is constant. In this case, attractiveness is no more distance dependent. As a result, a flashing firefly can be seen from anywhere in the domain. This situation is particularly useful to reach a single (usually global) optimum. This particular behavior of the algorithm corresponds to a special case of particle swarm optimization method. On the other hand, when $\gamma \rightarrow \infty$, then we have $\beta(r) \rightarrow \delta(r)$, which is a Dirac δ - function. This situation implies that the attractiveness of an individual firefly is almost zero to others. As a result, each firefly roams in a completely random way. This behavior corresponds to random search method. In case of multiple optima, adjusting γ can be useful.

Algorithm 1 presents the pseudo code of the firefly algorithm.

3.3 Gain tuning approach

Let us consider the original signal as $y(t)$. The objective of the tuning is to find the values of the gains α , k_1 and k_2 , such that the derivative estimate $\hat{y}(t)$ approaches to $\dot{y}(t)$ in a reasonable time. However, in the noisy case, since exact convergence is not possible, then the objective is to minimize the error as much as possible. To achieve this goal, the following objective function will be considered:

$$J = \min \int_0^{t_{sim}} \left| \left(\hat{y}(t) - \dot{y}(t) \right) \right| dt \quad (13)$$

such that, $lb \leq \mathbf{x} \leq ub$

$$|\nu(t)| \leq \mu$$

where, t_{sim} is the simulation time, vector \mathbf{x} contains the optimization variables *i.e.* gains of the differentiators, lb is the lower bound of the gains, ub is the upper bound of the gains, $\nu(t)$ is the measurement noise and μ is the bound on measurement

Algorithm 1 Firefly algorithm

Objective function $f(\mathbf{x})$, $\mathbf{x} = (x_1, \dots, x_d)^T$.

Generate an initial population of n fireflies

\mathbf{x}_i ($i = 1, 2, \dots, n$).

Light intensity I_i at \mathbf{x}_i is determined by $f(\mathbf{x}_i)$.

Define light absorption coefficient γ .

while ($t < \text{MaxGeneration}$),

for $i = 1 : n$ (all n fireflies)

for $j = 1 : n$ (all n fireflies) (inner loop)

if ($I_i < I_j$)

 Move firefly i towards j

end if

 Vary attractiveness via $\exp[-\gamma r^2]$.

 Evaluate new solutions and update I_i .

end for j

end for i

Rank the fireflies and find the current global best \mathbf{g}_* .

end while

post-process results and visualizations

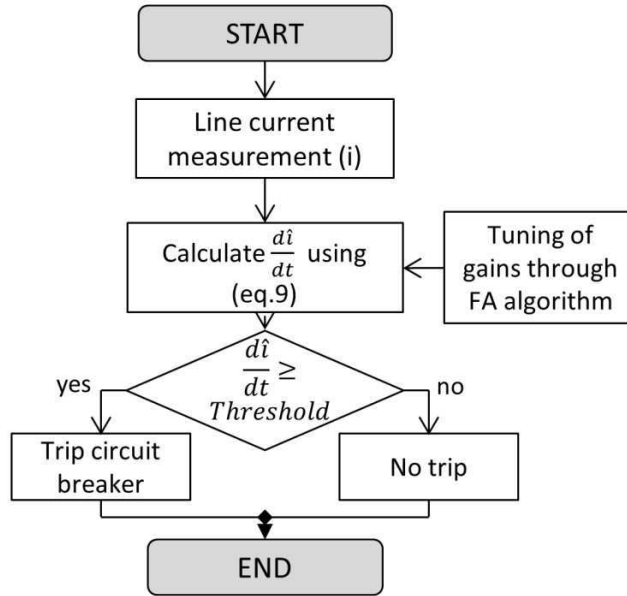


Figure 2. Flow-chart of the proposed derivative estimation based DC microgrid protection scheme

noise. simulation studies have been done to optimize the gains on a noisy test signal through FA optimization.

The main idea of the proposed scheme is as follows: From the noisy line current measurement, the derivative of line current in eq. (5) is estimated through discrete time sliding mode differentiator of eq. (9). The parameters of the differentiator are tuned through Firefly algorithm based optimization technique. If the estimated line current derivative exceeds a predefined threshold, then the system will detect the fault and a trip signal will be send to the breaker. If the estimated derivative is below the thresholds, then no trip signal will be transmitted. The flow-chart in Fig. 2 summarizes the above mentioned main idea.

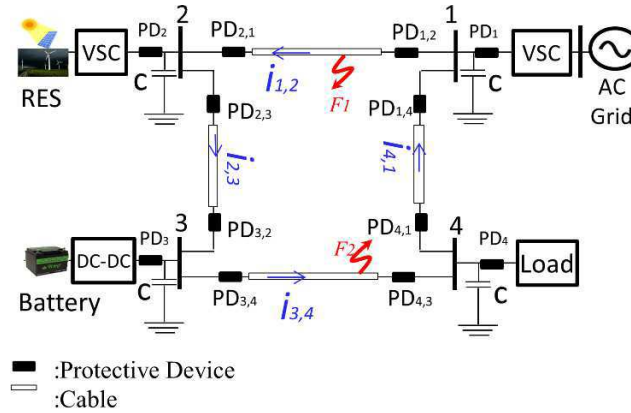


Figure 3. DC microgrid structure

4 Applications

4.1 System configuration

In this work, loop type DC microgrid will be considered for the design of the protection system. The microgrid under consideration can be seen in Fig. 3. The microgrid consists of the following elements as found in the literature:

- Distributed generation: Solar Photo Voltaic (PV) connected through a DC-DC converter, or wind turbine using Permanent Magnet Synchronous Generator (PMSG) connected through a VSC. Both the converters work on the principle of maximum power point tracking from the sources.
- Loads: Constant resistance type of DC loads are used in this system
- Energy storage system: To take care of load and generation unbalance, energy storage system is used. In this work, Battery Energy Storage System (BESS) has been considered, which is connected through a bi-directional DC-DC converter.

The power and component ratings of all the modules are given in Table 1. In this

Table 1. Rating of DC microgrid components

Parameters	Values
DC Grid Voltage	1200 V
Base Power	1 MW
Battery DC-DC Converter	1 MW
Renewable energy VSC	1 MW
GRID VSC	1 MW
Cable Resistance	8 m Ω per Km
Cable Inductance	7 μH per Km
Filter Capacitor, C	25 mF
Load	Constant impedance load 1 MW

system, all converter topologies incorporate protection of IGBTs but not the diodes. In such a case, if a fault on DC bus is not cleared within 2 ms, then freewheeling diodes and other sensitive network components may get damaged.

4.2 Results and discussions

In this section, various cases will be studied to check the robustness the proposed protection scheme. First, the result of gain tuning will be considered in Section 4.2.1. The optimized gains differentiator will then be compared with non-optimized gains case and also with classical method like Euler's method. The optimized gain differentiator will then be used for the detection of fault in DC microgrid in Section 4.2.2. Here, two cases will be considered depending on the load conditions. In case-1, the load will be considered relatively low i.e. 0.13p.u. In case-2, high load of 1p.u. will be considered. Finally, this part of the article will end with a comparative analysis of the proposed technique with existing differential protection scheme for different loading conditions.

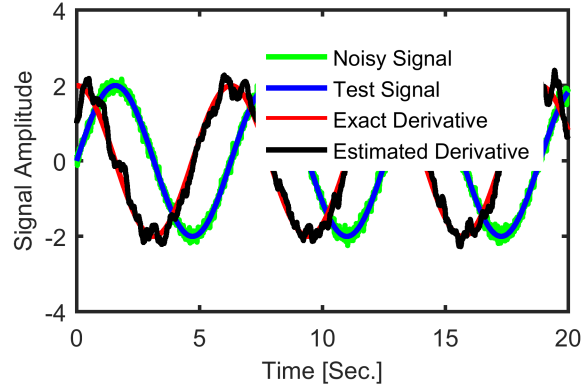


Figure 4. Noisy test signal and its derivative estimation

4.2.1 Gain tuning results Simulation studies have been done to optimize the gains of our differentiator on a noisy test signal through FA optimization. For this purpose, let us consider our test signal is $2\sin(t)$. Next, we have corrupted the signal with Gaussian noise. Although the test signal has low frequency, but the presence of high frequency noise makes it a suitable alternative of actual noise present in the DC power system. The exact derivative in our case is $2\cos(t)$. So, the objective of gain tuning is to find values of α , k_1 and k_2 such that the derivative estimation (eq. (9)) approaches to as close as possible to the exact derivative using cost function J . The result of the simulation of this process can be seen in Fig. 4. From the simulation results it can be concluded that the estimated derivative is very close to the exact derivative *i.e.* $2\cos(t)$ in spite of having very noisy original signal. In order to better check the performance of the continuous finite-time convergent differentiator, a comparison has been done with Euler method of differentiation. The result can be seen in Fig. 5. This result shows that in the presence of noise, the Euler method of derivative estimation fails completely. While the method being used in our work provides very good estimation of the derivative.

Next a comparison of the differentiator with optimized gains and non-optimized gains have been done on a different test signal to check the robustness of the optimized differentiator gains. This can be seen in Fig. 6. From this figure, it can be seen that the optimized gain output of the differentiator is more close to the analytical derivative. Moreover, it is smoother than the output in the case of non-optimized gains. This validates the application of the optimization technique along with the effectiveness of the differentiation approach. The evolution of the cost function J can be seen in Fig 7. Fig. 7 also provides a comparison of the objective function evaluation (13) obtained through FA optimization and Particle Swarm optimization technique (PSO). Comparative result shows that FA performed better than PSO for this particular application. Finally the optimized gains: $\alpha = 0.96$, $k_1 = 4$ and $k_2 = 44.7$. The gains were obtained offline. So, computational time needed for the optimization is not an issue in our case. However, the selected gains may not provide the optimal performance in every operating conditions. In such a case, regular offline tuning can be done w.r.t. various test signals to improve the performance of the proposed fault detection techniques. In the context of power system, regular offline updating of model parameter is not unusual [32].

4.2.2 Fault detection results In this part, the improvement of the existing line current differential protection scheme will be shown through Matlab/Simulink $\text{\textcircled{R}}$ based simulations. As mentioned in the introduction, in this work, only primary protections will be considered. Secondary protection can be easily provided and avoided here for brevity. Protection device (PD) consists of digital relay, which gives trip to a circuit breaker in case of a fault. Digital relays are equipped with micro-controllers for setting thresholds, analog to digital transformation of measurements,

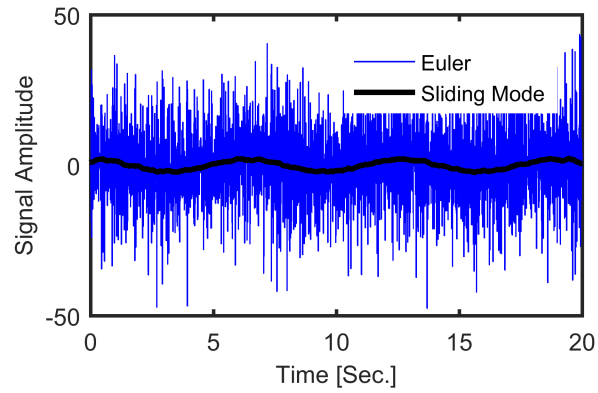


Figure 5. Comparison of derivative estimation, Euler method and eq. (7). Blue - Euler, black - eq. (7).

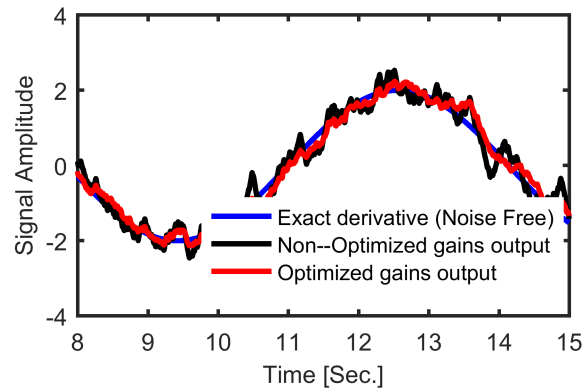


Figure 6. Comparison of the output of the differentiator with optimized and non-optimized gains.

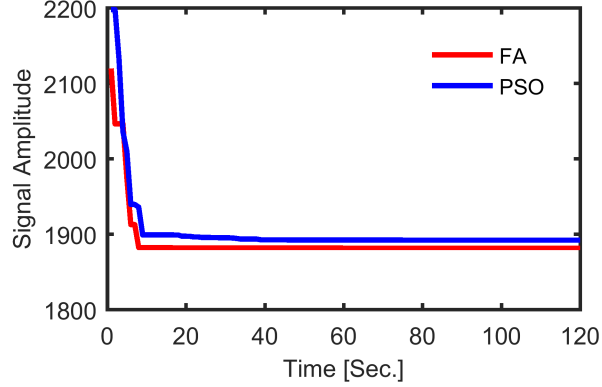


Figure 7. Evolution of the cost function J (13)

calculating $\Delta i/\Delta t$ etc. If $\Delta i/\Delta t$ exceeds the thresholds, then the relay sends a trip signal to circuit breakers.

To test the effectiveness of the proposed approach *i.e.* optimized current differential scheme (OCDS), it will be tested with two different loading conditions. They are given below:

Case-1: Let us consider fault F_1 (Fig. 3) at $t = 1$ sec. while load is 0.13p.u. The response of the system, after the fault can be seen in Fig. 8 . High transient current and sudden voltage drop of the system originated from the fault can be seen in Fig. 8. The protection system must have to be capable of clearing the fault by activating the circuit breaker before the current reaches to high value to destroy the cable for example. Which means, the detection have to be very rapid.

After the fault, as the amplitude of the line current increases, the proposed protection system (Fig. 2) automatically detects the high value of $|\frac{\Delta i}{\Delta t}|$ through eq. (9) and sends trip signal to the circuit breaker in a very short period of time *i.e.* $200\mu s$. The measurement noise is bounded by $\pm 20\%$ of the signal in p.u. A comparison of the trip signal generated by the proposed work and that of existing

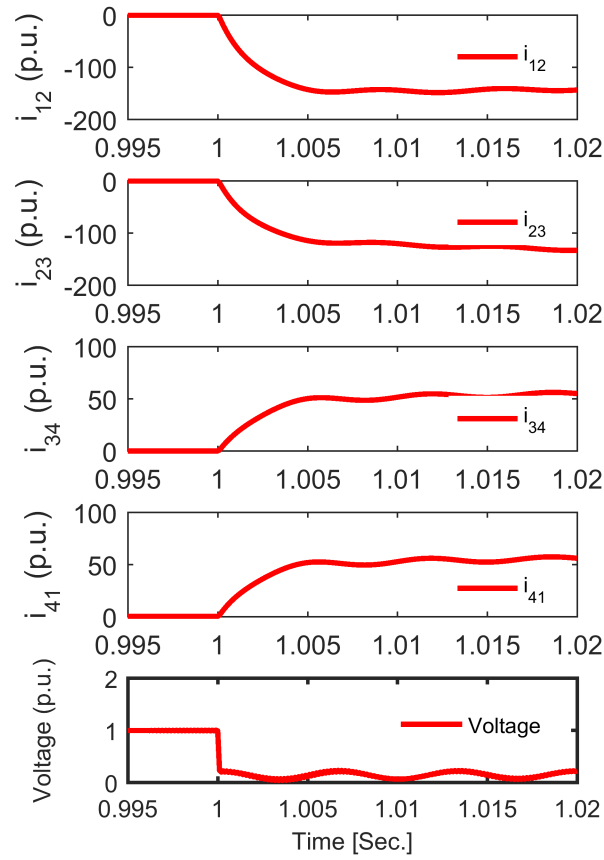


Figure 8. Line currents and bus voltage response for fault F occurred at $t = 1$ sec.

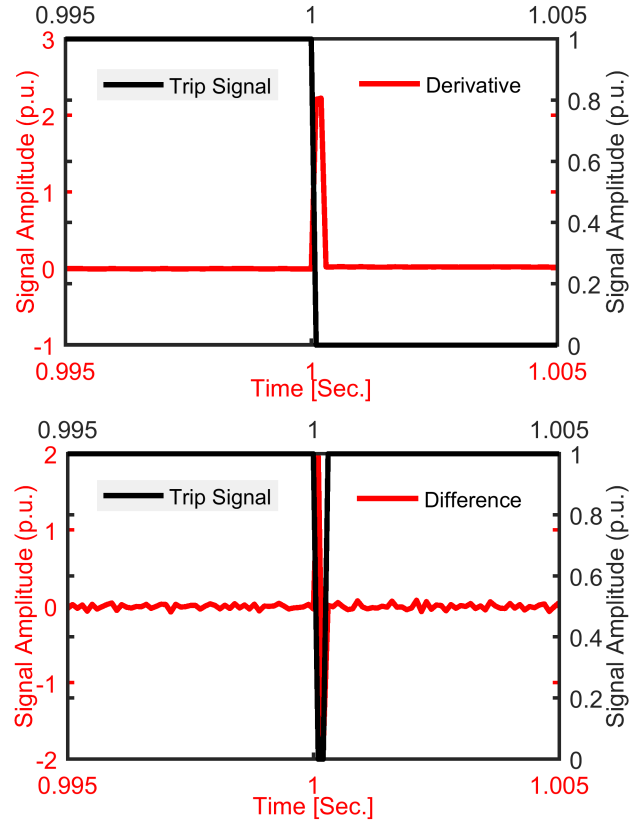


Figure 9. Trip signal and estimated derivative(difference) when noise is $\pm 20\%$ of the signal in p.u. (top- OCDS, bottom- line current differential protection scheme)

line current differential protection scheme can be seen in Fig. 9 . Fig. 9 also shows the difference and derivative signal. From Fig. 9, it can be claimed that the proposed method outperform the existing line current differential protection scheme. The proposed method did not give any false alarm or didn't miss anything because of its robustness to measurement noise. Although existing line current differential protection scheme initially detect the fault and gave the alarm but it returned back immediately to no fault state because of being highly sensitive to noise. This situation is undesirable. This may lead to disastrous outcome like burning the element

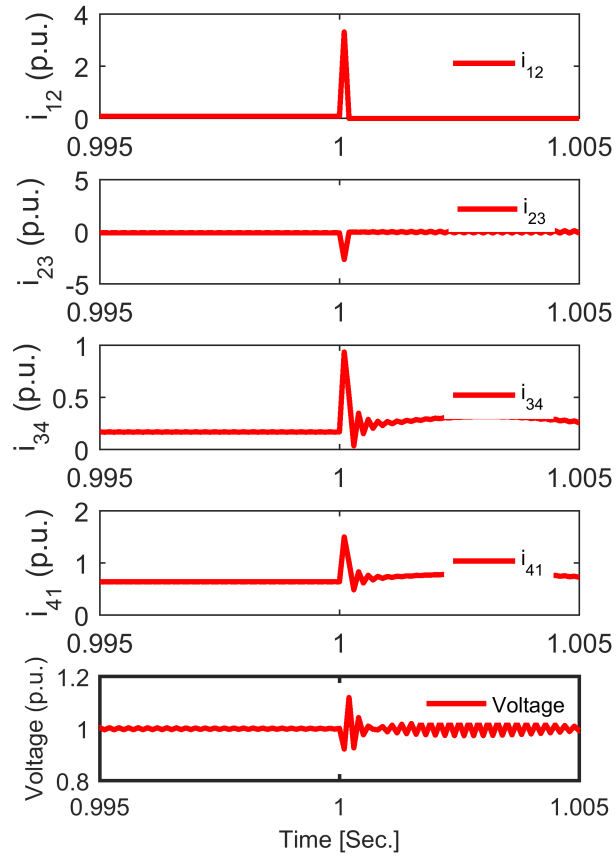


Figure 10. Line currents and voltage before, during and after the clearance of fault for fault, F .

being protected. With the proposed protection method, the microgrid returns back to its normal operation after the clearance of the fault. The voltage at the grid and the line currents during and after fault clearance can be seen in Fig. 10.

Case-2: Next, for the same fault but at different loading conditions, the proposed scheme is checked. In this case, the load is 1p.u. The measurement noise is bounded by $\pm 20\%$ of the signal in p.u. like the previous case. A comparison of the

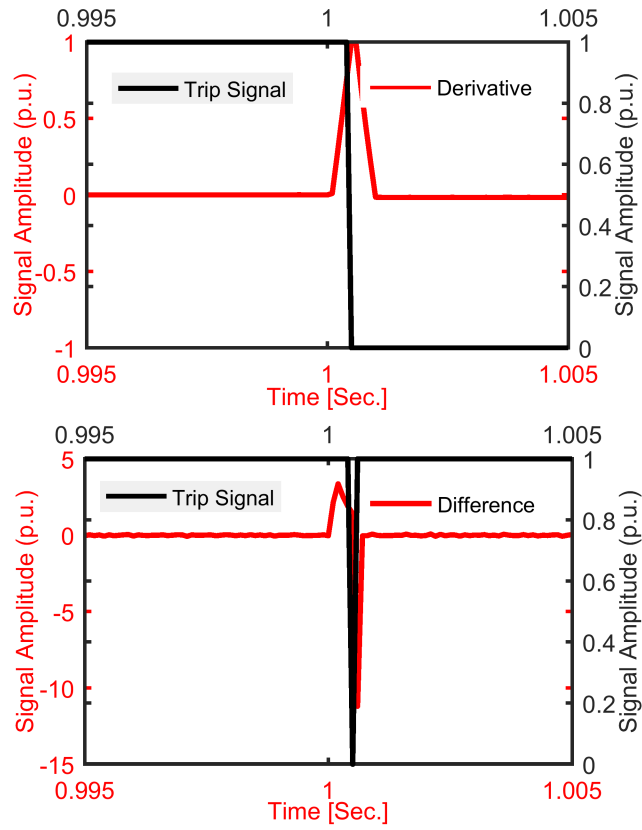


Figure 11. Trip signal and estimated derivative(difference) when noise is $\pm 20\%$ of the signal in p.u. with load as 1p.u. (top- OCDS, bottom- line current differential protection scheme)

trip signal generated by the proposed work and that of existing line current differential protection scheme can be seen in Fig. 11. This simulation result also shows the performance improvement by the proposed method to existing differential current protection scheme. Existing method gives false alarm due to noise sensitivity while proposed method is free from false alarm. The voltage at the grid and the line currents during and after fault clearance can be seen in Fig. 12.

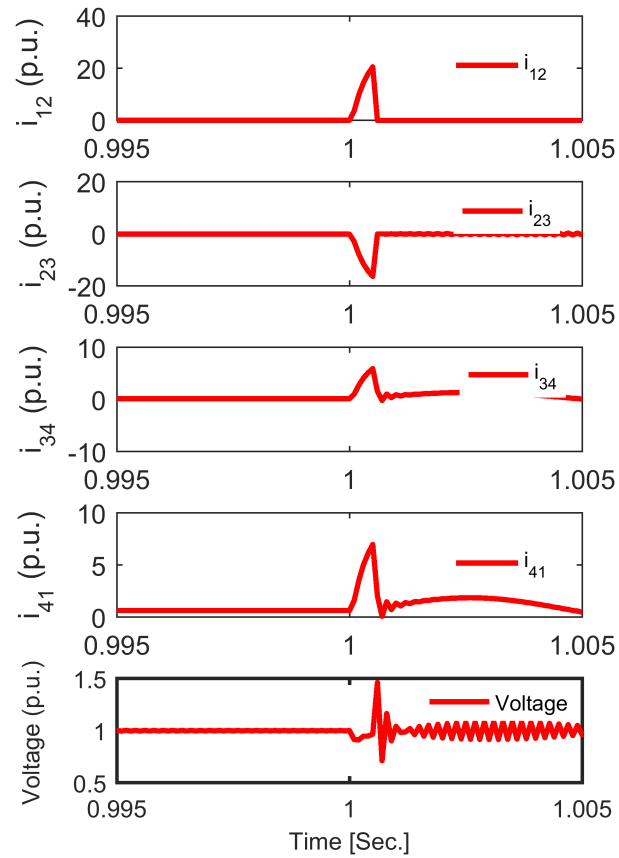


Figure 12. Line currents and voltage before, during and after the clearance of fault for fault, F_1 with 1p.u. load.

Similar result were obtained in the case of fault F_2 . However, the results are omitted here for maximum number of figures limitation.

4.3 Comparative analysis

From the comparative simulation results presented before, few conclusions can be drawn about this work. First of all, this work presents a very simple fault detection approach by considering noisy measurements that respect the time limit mentioned in [21]. Secondly, the proposed approach do not give false alarm which is an improvement of the existing line current differential protection scheme. Thirdly, this paper do not require neither any master-slave configuration like [18] nor any communication link between the two sides of the element being protected like [17]. Fourthly, the proposed approach is robust to bounded noise unlike the others approach. Finally, this paper uses modern meta-heuristic optimization approach to tune the gain of the algorithm which simplifies the algorithm design.

5 Conclusions

This paper concentrates on one of the important criteria of DC microgrid topology selection *i.e.* well functioning protection system. Through analytical calculations it was shown that the line current derivative can be considered as a fault signatures. Then the proposed method calculate the time derivative of noisy line current through continuous finite-time convergent differentiation scheme and use it for the purpose of fault detection. The proposed method is robust, fast and accurate. The proposed approach is based on loop-type microgrid and can be extended to various other types of microgrid. Simulations results verified the better performance of

the proposed method to a very popular DC microgrid protection scheme *i.e.* line current differential protection scheme .

In future, the ideas presented in this article can be extended in multiple ways. For example, it was considered that all the lines were connected. However, one or more lines can be open due to maintenance. Also, variation in the power of energy storage was not considered. Moreover, due to various conditions, renewable energy might not provide any power. What are the impact of all these factors in detecting the fault can be considered in the future. Also, in the calculation of $\frac{di}{dt}$, the initial current has been ignored. This can be problematic in certain conditions during high impedance fault. In future, this will be considered. Moreover, derivative based fault detection scheme can be very sensitive if a capacitor or load or motor is switched in the circuit. In future work, this impact will be studied to analyze the sensitivity of derivative based fault detection scheme.

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