UDC 621.3 https://doi.org/10.20998/2074-272X.2023.2.10

A. Jani, V.H. Makwana

Modified discrete Fourier transform algorithm for protection of shunt compensated distribution line

Introduction. *The response time of the relay plays vital role when fault occurs on the line. Various algorithms are adopted to increase the sampling rate of the relay which, in turn, improves the response time.* ***Methods****. Discrete Fourier transform and modified discrete Fourier transform are the two algorithms used to calculate the fundamental frequency phasor of the signal required by the relay to initiate trip command. It is known that discrete Fourier transform takes four to five cycles to produce the fundamental frequency phasor but it fails to deal with the decaying DC component. On the other hand, modified discrete Fourier transform improves the response time by removing the decaying DC component along with the other harmonics in just one cycle and a few samples. The* ***aim*** *of this paper is to cover discrete Fourier transform and modified discrete Fourier transform algorithms to analyze the performance of the three overcurrent and one earth fault relaying scheme for different types of faults occurring in the distribution system.* ***Methodology****. The concept of three overcurrent and one earth fault scheme is also explained in this paper for protection of shunt-compensated distribution system. The scheme is designed for variable power factor. MATLAB/Simulink is used as the software tool to validate the results obtained for various types of faults occurring in the system. The* ***results*** *are represented graphically to illustrate the time of response of the protection scheme when shunt compensators are connected at the receiving end of distribution network.* References 16, tables 2, figures 8.

Key words: **modified discrete Fourier transform, three overcurrent and one earth fault protection scheme, shunt compensation, distribution system, response time of relay.**

Вступ*. Час спрацювання реле відіграє життєво важливу роль при виникненні несправності на лінії. Для збільшення частоти дискретизації реле застосовуються різні алгоритми, що, своєю чергою, покращує час спрацювання.* ***Методи****. Дискретне перетворення Фур'є та модифіковане дискретне перетворення Фур'є – це два алгоритми, які використовуються для розрахунку вектора основної частоти сигналу, необхідного для реле подачі команди на відключення. Відомо, що для отримання вектора основної частоти дискретного перетворення Фур'є потрібно від чотирьох до п'яти циклів, але воно не справляється з постійною складовою струму, що згасає. З іншого боку, модифіковане дискретне перетворення Фур'є покращує час спрацювання, видаляючи постійну складову струму, що згасає, разом з іншими гармоніками всього за один цикл і кілька вибірок.* ***Мета*** *цієї статті полягає в тому, щоб охопити алгоритми дискретного перетворення Фур'є та модифікованого дискретного перетворення Фур'є для аналізу характеристик трьох схем реле максимального струму та однієї схеми захисту від замикань на землю для різних типів несправностей, що виникають у розподільчій системі.* ***Методологія****. У статті пояснюється також концепція трьох схем перевантаження по струму і однієї схеми замикання на землю для захисту розподільчої системи з паралельною компенсацією. Схема розрахована на змінний коефіцієнт потужності. MATLAB/Simulink використовується як програмний інструмент для перевірки результатів, отриманих для різних типів відмов, що виникають у системі.* ***Результати*** *представлені графічно, щоб проілюструвати час спрацьовування схеми захисту, коли шунтуючі компенсатори підключені на приймальному кінці розподільної мережі.* Бібл. 16, табл. 2, рис. 8.

Ключові слова: **модифіковане дискретне перетворення Фур'є, три схеми максимального струмового захисту та одна схема захисту від замикань на землю, паралельна компенсація, розподільна система, час спрацювання реле.**

Introduction. Protection of distribution system is the most vulnerable part of the power system protection because it often encounters severe dynamic changes due to change in line loading and uncertainty in power factor [1, 2]. Further, the severity intensifies under abnormal conditions like faults occurring in the network. Such changes are generally dealt with the use of reactive power compensators in the line, which possess controllers and power electronic components [3]. The presence of compensators introduces error in the measurement of fault and system parameters [4, 5]. Hence, the protection scheme needs to be fast and sensitive enough to operate efficiently under all these conditions.

Variation in line loading in distribution network is a major challenge for a relay present at receiving end of the line [5]. Generally, the distribution network is protected by overcurrent and earth-fault relays in the first zone of protection. The most common type of protection scheme used for distribution lines is three overcurrent and one earth-fault (3 O/C & 1 E/F) protection scheme [6]. The protection devices have to be selected carefully and must comply with consonant standards as far as industrial and commercial loads are considered. The presence of distributed generation, for example, may lead to additional challenges to be faced by the relay, where the power flows in both the ways. Such situations demand dynamic settings of the relay, as illustrated in [2].

The time of response of the protection algorithm decides the sensitivity of the relay, which needs to be as high as possible [7]. Earlier the researchers used to apply mimic filters and other such digital filtering techniques in order to damp out the decaying DC component from the current signal required by the relay [7, 8]. Though, due to the disadvantages of these filters, the researchers developed Discrete Fourier Transform (DFT) algorithm to obtain the fundamental component of line current to be fed to the relay [9]. The DFT algorithm usually takes a few cycles to serve the required purpose which makes the protection algorithm slow and erroneous. Thus, Modified Discrete Fourier Transform (MDFT) was proposed in [7, 8] which is capable to produce the fundamental component of current in one cycle and a few samples, thereby, decreasing the response time of the relay.

A number of researchers have proposed optimal techniques of relay coordination using various types of overcurrent relays [1, 3, 10]. Since this paper is designed for education purpose, it covers the basic concepts of shunt compensation and overcurrent protection. The focus of this paper is to illustrate the performance of 3 O/C & 1 E/F protection scheme under different fault conditions, considering the shunt compensators such as Fixed Capacitor Thyristor Controlled Reactor (FCTCR) and Distributed Static Synchronous Compensator (DSTATCOM). The results are obtained using both, DFT and MDFT, algorithms and the comparison between the two algorithms is also explained in the sections below.

Protection of distribution line using overcurrent relay. Overcurrent is defined as very high current flowing through the line during any fault or abnormal conditions. An overcurrent relay is set to operate when the line current exceeds the threshold limit of the current, called plug setting of the relay. The family of overcurrent relays includes instantaneous, time-delayed, definite time and inverse time overcurrent relays. Inverse-time relays are further classified as normal-inverse, very-inverse, and extremely-inverse.

Instantaneous relays operate within 1-2 cycles when fault occurs in the network. It is generally set to provide protection against short circuit, and hence, it is set for very high values of rated current (may be five times of rated current). Time-delayed relays are used to achieve the features of back-up protection and selectivity in relays.

Definite time relay is set to operate after a definite set time when the current exceeds the pick-up value. The pick-up setting of this relay is generally between 50 to 200 % of rated relay current and these relays are used to protect the radial feeders. In inverse-time overcurrent relays, the operating time of the relay is inversely proportional to the relay current. They are broadly categorized as phase-fault relays and earth-fault relays. For phase relays, the relay setting range is 50-200 % of rated relay current. Earth-fault relays are installed in order to sense the sensitive ground faults, having setting range 5-20 %, 10-40 % or 20-80 % of current transformer (CT) secondary rating, depending upon the sensitivity of the relay required. The generalized relation to define a standard overcurrent relay, given in (1), is written as:

$$t = \frac{\beta}{(PSM)^{\alpha} - 1} \cdot TMS \,, \tag{1}$$

where t is the time of operation of relay; PSM is the plug setting multiplier of relay; TMS is the time multiplier setting of the relay. The constants α and β are selected according to the Table 1 for various characteristics [6].

Table 1

Value of α and β for different inverse-time relays

Relay	α	β
Normal inverse	0.02	0.14
Very inverse	1	13.5
Extremely inverse	2	80

Figure 1 shows the operating characteristics of different overcurrent relays discussed in this section.

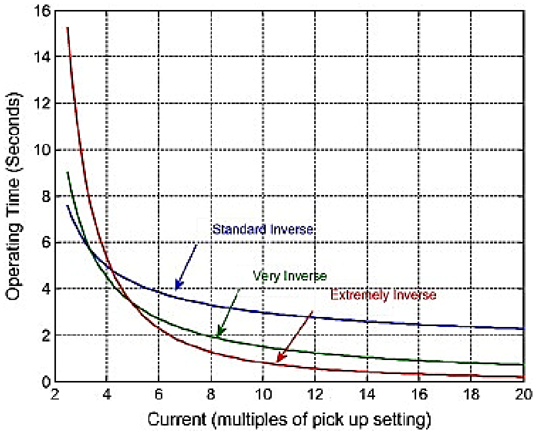


Fig. 1. Characteristics of different types of overcurrent relays

Three overcurrent and one earth-fault relaying scheme. Figure 2 illustrates the schematic diagram of the protection scheme used in this paper to demonstrate the protection of shunt compensated distribution line [6].

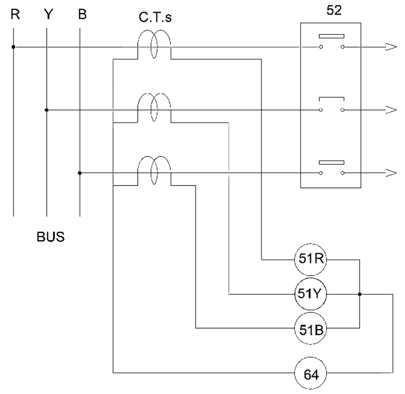


Fig. 2. Schematic diagram of 3 O/C & 1 E/F relaying scheme

In this figure, 51, 52 and 64 denote the international codes used for drawing the protection circuits. 51R, 51Y, 51B stands for overcurrent relays connected in R, Y and B phases of the line, respectively. Further, 52 stands for circuit breaker and 64 stands for earth-fault relay.

The relays used in this paper are set according to the above discussion. When phase faults occur in the line (R-Y, Y-B, R-B, R-Y-B), at least one of the three overcurrent relays shall sense the fault and operate according to the relay settings, following the set characteristics. In the case of phase-to-ground fault (R-g, Y-g, B-g), the residual current follows the path of earth-fault relay, which operates as per the relay settings. However, for double line-to-ground faults (R-Y-g, Y-B-g, R-B-g), both the phase overcurrent relays and the earth-fault relay will sense the fault and operate simultaneously.

Figure 3 describes the flowchart of the relay operation.

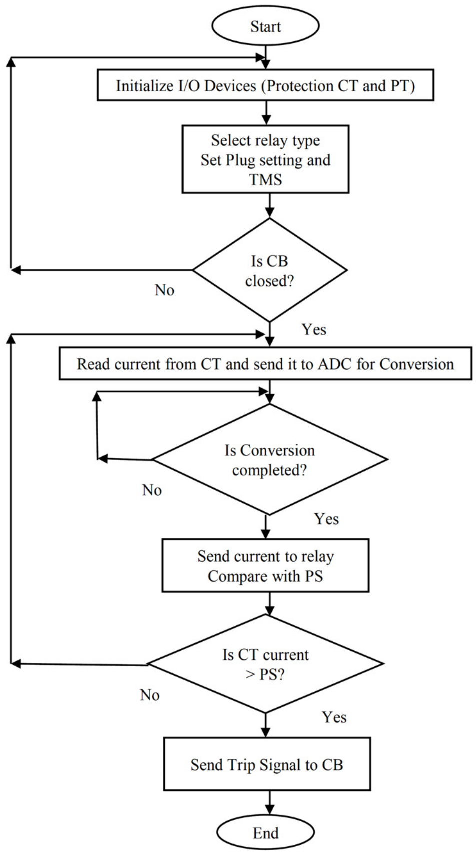


Fig. 3. Flowchart of relay operation

The line parameters are measured at regular intervals using protective current and potential transformers (CTs and PTs). These parameters are then given to the relay as input, where the input signal is first compared with the plug setting of the relay. If the measured current exceeds the set current, then trip signal is generated using mathematical and logical units; otherwise, uninterrupted supply is continued to be supplied to the line.

Protection of shunt compensated distribution line. Figure 4 shows the block diagram of the distribution network protected by 3 O/C & 1 E/F relaying scheme. For MATLAB simulation, 11 kV, 50 Hz radial distribution network, feeding a three-phase load, is considered in this paper. The parameter measurement block measures line current and sends it to the relay logic block. The relay logic block having 3 O/C & 1 E/F relaying logic (as shown in Fig. 3), sends trip signal to the circuit breaker under fault or other abnormal conditions.

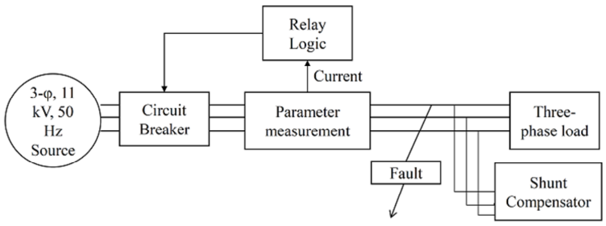


Fig. 4. Block diagram of the circuit used for analysis

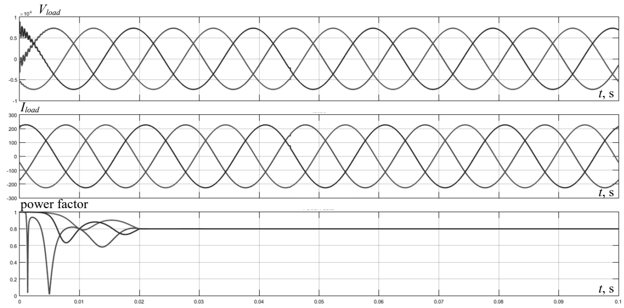
Shunt compensators installed in the distribution network. The presence of shunt compensators introduces power disturbances in the measurement of line parameters [11-13], which affects the reach of the relay [14, 15]. Hence, the relay settings need to be adjusted when reactive power compensators are installed to the line to be protected, to avoid mal-operation of main and back-up protection scheme.

Compensation can be either active or passive. Fixed inductors and capacitors providing a fixed percentage of reactive power compensation constitute passive compensators. However, the Static Var Compensators (SVC) and DSTATCOM, which are designed to compensate for variable reactive power demands, constitute active compensators. SVCs comprise of Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TSC), Fixed Capacitor TCR (FCTCR), TSC-TCR etc. This paper covers the analysis of FCTCR and DSTATCOM.

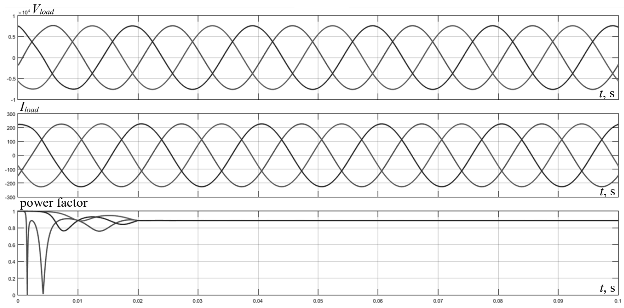
Removal of decaying DC component from input signal. Under normal conditions, the voltage and current signals contain only fundamental and integer harmonic components. The DFT filtering algorithm produces the fundamental component within one cycle for such cases. But when fault occurs, the decaying DC component is also present along with the fundamental and harmonic components. The convergence speed of DFT algorithm reduces to more than 4 cycles due to the presence of decaying DC component. Thus, a MDFT technique is proposed by researchers [8, 9], which takes one cycle and a few samples to produce the fundamental signal during fault condition. It reduces the response time of the relay.

Results and discussions. The algorithm of 3 O/C & 1 E/F relaying scheme is simulated in MATLAB using 11 kV, 50 Hz distribution substation feeding a 3 MW, 0.8 power factor three-phase load. A shunt compensator is installed at the receiving end to improve the power factor from 0.8 to 0.9. Here, results for FCTCR and DSTATCOM are shown in this paper. The relay operation is verified against various phase and ground faults, like L-g, L-L, L-L-g, L-L-L and L-L-L-g. The distribution line length is considered as 20 km.

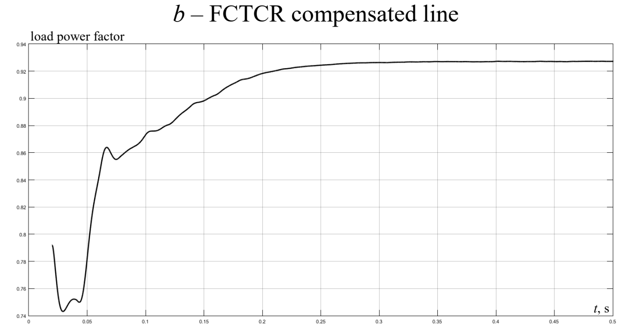
Power factor correction using FCTCR and DSTATCOM. Both the FCTCR and DSTATCOM are designed to improve the power factor from 0.8 to 0.9. The design is verified in Simulink and provides adequate results, as shown in Fig. 5. Figure 5,*a* shows the voltage, current and power factor of the load for uncompensated line. It can be noticed that the power factor is maintained at 0.8. Figure 5,*b* depicts that the power factor for FCTCR-compensated line has increased to 0.9. Similar is the case in Fig. 5,*c*, where the power factor of DSTATCOM-compensated line is improved to approximately 0.9.



a – without compensation



b – FCTCR compensated line

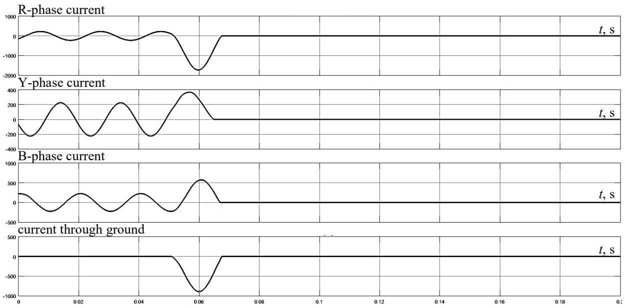


c – DSTATCOM compensated line

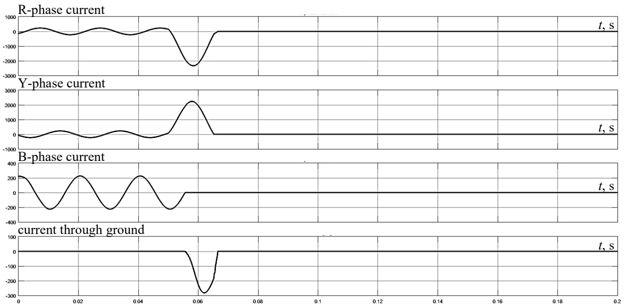
Fig. 5. Power factor improvement using FACTS devices

Fault occurring on the shunt compensated distribution network. Figure 6 shows the relay tripping action for L-g, L-L, L-L-g, L-L-L and L-L-L-g faults occurring in a FCTCR-compensated distribution network. Figure 6 consists of six graphs and each graph comprises of three curves of current flowing through R, Y and B phases of the line. It is observed from the simulation results that the E/F relay operates along with the O/C relays only for ground faults. For all other faults, only O/C relay operates.

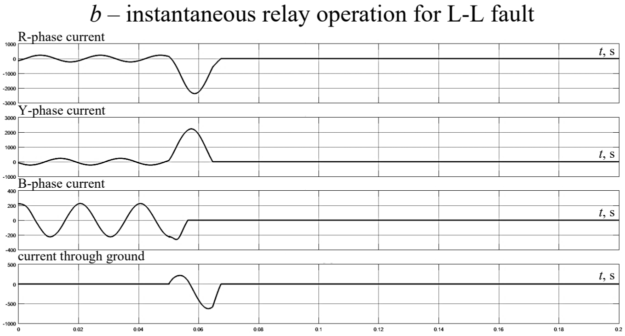
The high value of current in the faulted phase of the line implies that the fault has occurred in that particular phase. Accordingly, the overcurrent relay corresponding to the faulted phase will trip the supply to all the three phases. This setting is done because if the breaker is set to trip the faulted phase in the simulation, then some residual fault current flows to the healthy phases of the line, giving erroneous results. The reason for this error is the internal grounding of the elements used in the simulation, which provides a path to the fault current [16].



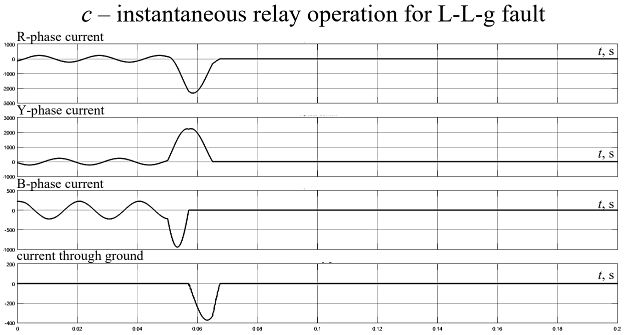
a – instantaneous relay operation for L-g fault



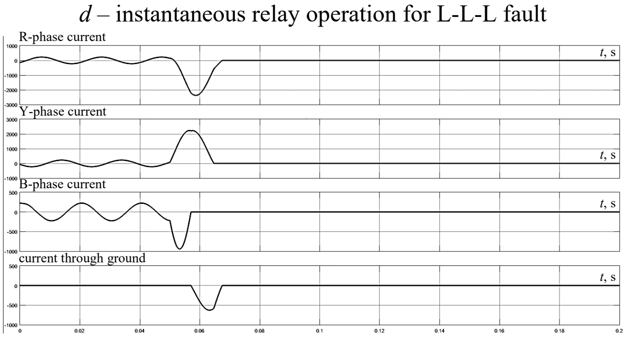
b – instantaneous relay operation for L-L fault



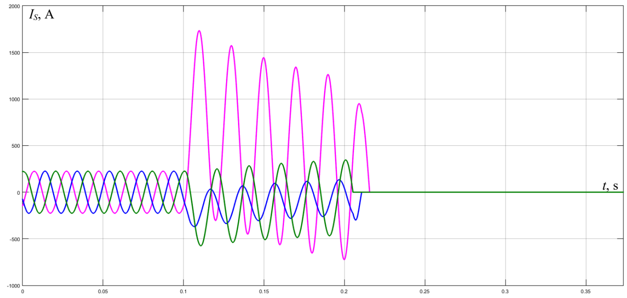
c – instantaneous relay operation for L-L-g fault



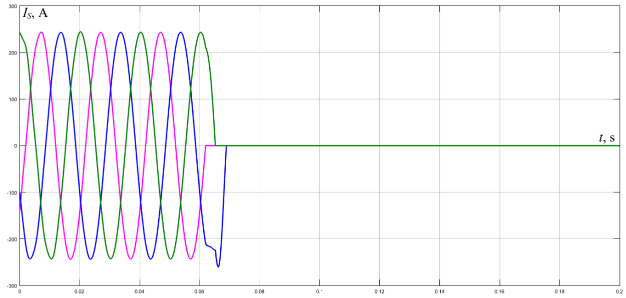
d – instantaneous relay operation for L-L-L fault



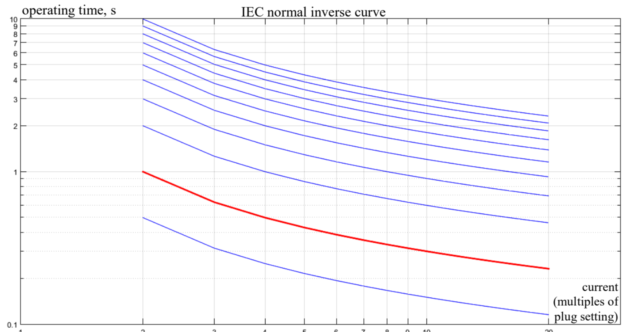
e – instantaneous relay operation for L-L-L-g fault



f – definite time relay operation for L-g fault



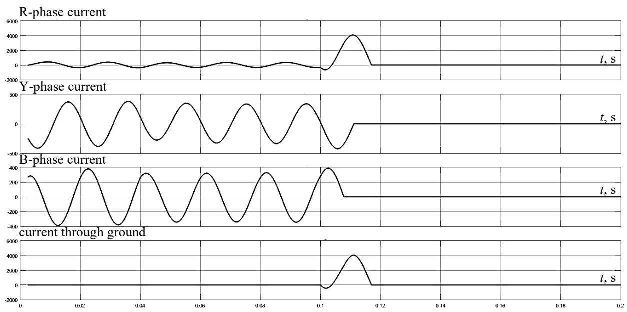
g – IDMT relay operation for L-g fault



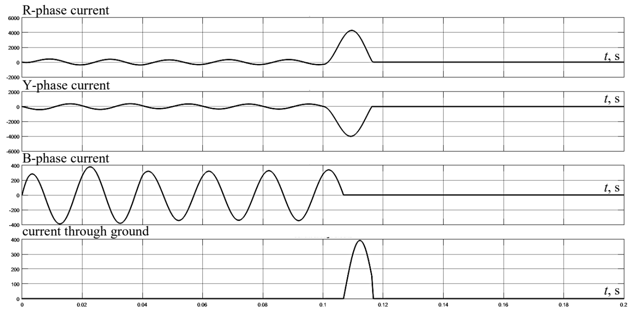
h – normal inverse characteristics of IDMT relay for (*e*)

Fig. 6. Different types of overcurrent relay characteristics for FCTCR-compensated line

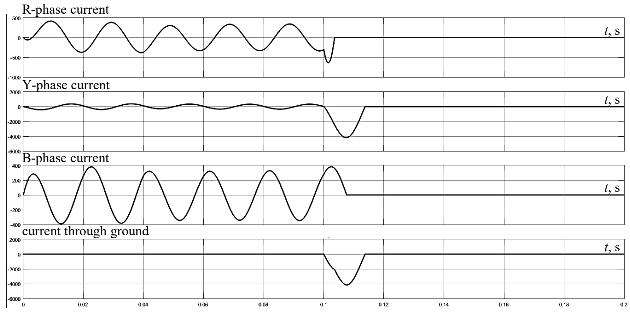
Similar results are obtained for DSTATCOM as well, as shown in Fig. 7. Since L-g fault is the most common fault, the results in this section include only L-g fault for definite time overcurrent relay and Inverse Definite Minimum Time (IDMT) relay. The relay is verified to operate accurately for other faults as well, though it is not included in this paper. It is observed that the definite time overcurrent relay sends the trip command after a set delay (0.1 s). In this case, the IDMT relay operates according to (1), when fault occurs on the line. The results are shown for normal-inverse characteristics. Other characteristics given in Table 1, such as very-inverse and extremely inverse, are also tested in MATLAB for FCTCR and DSTATCOM-compensated distribution network considered for simulation.



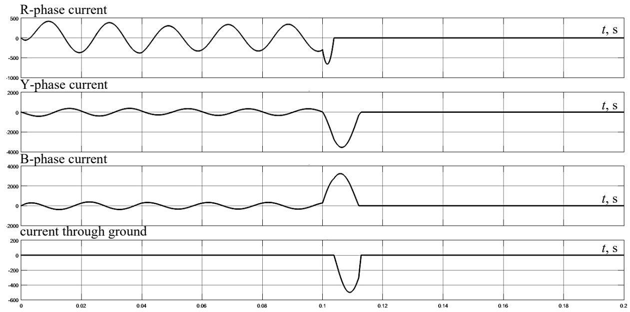
a – instantaneous relay operation for L-g fault



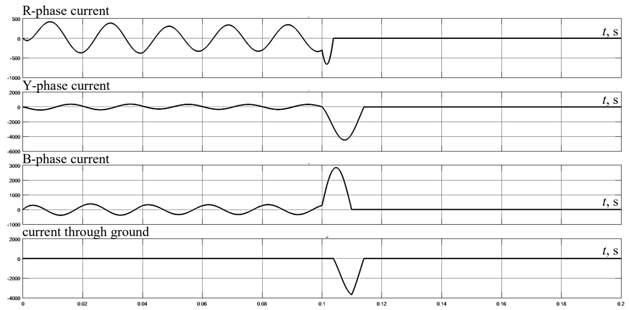
b – instantaneous relay operation for L-L fault



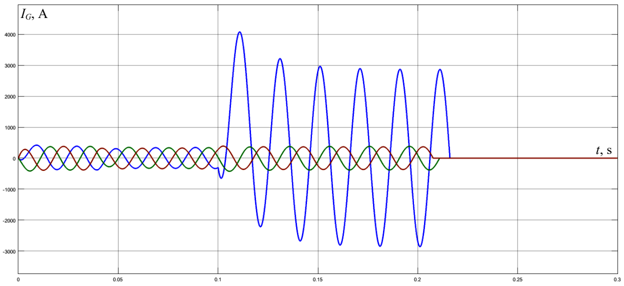
c – instantaneous relay operation for L-L-g fault



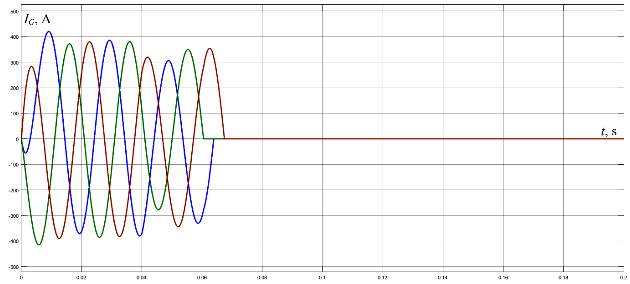
d – instantaneous relay operation for L-L-L fault



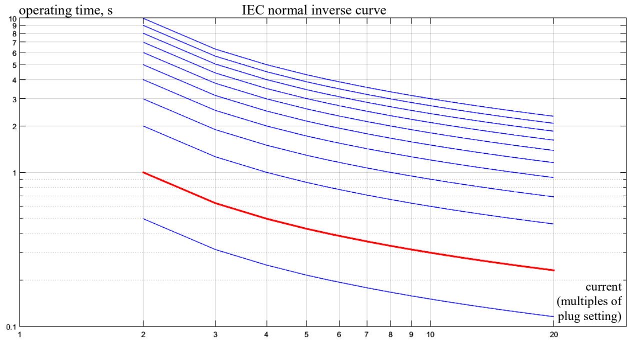
e – instantaneous relay operation for L-L-L-g fault



f – definite time relay operation for L-g fault



g – IDMT relay operation for L-g fault



h – normal inverse characteristics of IDMT relay for (*e*)

Fig. 7. Different types of overcurrent relay characteristics for DSTATCOM-compensated line

Based on the simulation results obtained, the operation of the 3 O/C & 1 E/F relaying scheme can be understood using Table 2, which depicts the combination of relays which operates depending upon the type of fault.

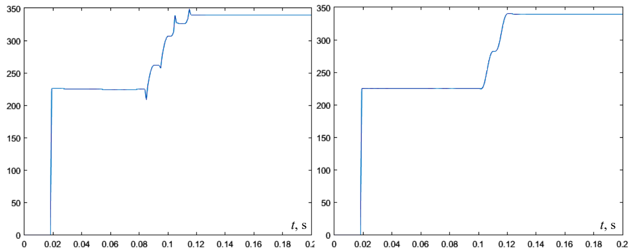
Table 2

Relay operation based on the type of fault

Fault	O/C Relay: Phase R	O/C Relay: Phase Y	O/C Relay: Phase B	E/F Relay
R-g	Yes	No	No	Yes
Y-g	No	Yes	No	Yes
B-g	No	No	Yes	Yes
R-Y	Yes	Yes	No	No
Y-B	No	Yes	Yes	No
R-B	Yes	No	Yes	No
R-Y-g	Yes	Yes	No	Yes
Y-B-g	No	Yes	Yes	Yes
R-B-g	Yes	No	Yes	Yes
R-Y-B	Yes	Yes	Yes	No
R-Y-B-g	Yes	Yes	Yes	Yes

Testing of MDFT algorithm for fast response of the relay. The results shown above are obtained by *V-I* measurement block in MATLAB/Simulink, which is based on Fast Fourier Transform (FFT) algorithm. It is mathematically proven that the output of DFT and FFT is same. FFT can do everything a DFT does, but more efficiently and much faster than a DFT. It's an efficient way of computing the DFT. Hence, the output of *V-I* measurement block can be considered as the DFT output.

Figure 8,*a*,*b* shows the output of DFT and MDFT algorithm, respectively, when L-g fault occurs in the simulation circuit considered above for the analysis. It is observed from the output that the magnitude of current is obtained after more than 2 cycles when fault occurs on the line (Fig. 8,*a*). However, MDFT (Fig. 8,*b*) produces the desired output in 1 cycle and a few samples, thereby, improving the time of response of the relaying algorithm.



a *b*

Fig. 8. Output response of DFT and MDFT for L-g fault at t = 80 ms

Conclusion. This paper discusses the basics and performance of the family of overcurrent relays, such as instantaneous, definite time and inverse definite minimum time relays, for a shunt compensated distribution network. The three overcurrent and one earth-fault protection scheme installed to protect the distribution network and the simulation results verify that the operation of the healthy phase is not affected by the asymmetric faults due to this scheme. Hence, it is concluded that this scheme is more reliable and accurate to protect the network. Also, the presence of static VAR compensators like fixed capacitor thyristor controlled reactor and distribution static synchronous compensator is taken in account and the protection scheme performs precisely against the faults on shunt compensated distribution line as well. Finally, the response time of the relaying algorithm is improved by modified discrete Fourier transform algorithm and the results are compared with conventional discrete Fourier transform which concludes that modified discrete Fourier transform produces the desired output within 1 cycle and a few samples whereas discrete Fourier transform takes more than 2 cycles for the same.

Conflict of interest. The authors declare that they have no conflicts of interest.

REFERENCES

1. Chandraratne C., Woo W.L., Logenthiran T., Naayagi R. T. Adaptive Overcurrent Protection for Power Systems with Distributed Generators. *2018 8th International Conference on Power and Energy Systems (ICPES)*, 2018, pp. 98-103. doi: https://doi.org/10.1109/ICPESYS.2018.8626908.

2. Mahindara V.R., Rodriguez D.F.C., Pujiantara M., Priyadi A., Purnomo M.H., Muljadi E. Practical Challenges of Inverse and Definite-Time Overcurrent Protection Coordination in Modern Industrial and Commercial Power Distribution System. *IEEE Transactions on Industry Applications*, 2021, vol. 57, no. 1, pp. 187-197. doi: https://doi.org/10.1109/TIA.2020.3030564.

3. Filomena A.D., Salim R.H., Resener M., Bretas A.S. Ground Distance Relaying With Fault-Resistance Compensation for Unbalanced Systems. *IEEE Transactions on Power Delivery*, 2008, vol. 23, no. 3, pp. 1319-1326. doi: https://doi.org/10.1109/TPWRD.2007.909210.

4. Albasri F., Sidhu T.S., Varma R. Impact of Shunt-FACTS on Distance Protection of Transmission Lines. *2006 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources*, 2006, pp. 249-256. doi: https://doi.org/10.1109/PSAMP.2006.285397.

5. Albasri F.A., Sidhu T.S., Varma R.K. Performance Comparison of Distance Protection Schemes for Shunt-FACTS Compensated Transmission Lines. *IEEE Transactions on Power Delivery*, 2007, vol. 22, no. 4, pp. 2116-2125. doi: https://doi.org/10.1109/TPWRD.2007.900283.

6. Oza Bhuvanesh A., Nirmalkumar C. Nair, Rashesh P. Mehta, Vijay H. Makwana. *Power system protection and switchgear. In Chapter 1: Introduction and Philosophy of a Protective Relaying System*. Tata McGraw Hill Education Private Limited, 2010.

7. Jyh-Cherng Gu, Sun-Li Yu. Removal of DC offset in current and voltage signals using a novel Fourier filter algorithm. *IEEE Transactions on Power Delivery*, 2000, vol. 15, no. 1, pp. 73-79. doi: https://doi.org/10.1109/61.847231.

8. Sun-Li Yu, Jyh-Cherng Gu. Removal of decaying DC in current and voltage signals using a modified Fourier filter algorithm. *IEEE Transactions on Power Delivery*, 2001, vol. 16, no. 3, pp. 372-379. doi: https://doi.org/10.1109/61.924813.

9. Chi-Shan Yu, Wen-Hui Chen. Removing decaying DC component in fault currents via a new modify discrete Fourier algorithm. *IEEE Power Engineering Society General Meeting*, 2005, pp. 1041-1046. doi: https://doi.org/10.1109/PES.2005.1489295.

10. Ghotbi-Maleki M., Chabanloo R.M., Zeineldin H.H., Hosseini Miangafsheh S.M. Design of Setting Group-Based Overcurrent Protection Scheme for Active Distribution Networks Using MILP. *IEEE Transactions on Smart Grid*, 2021, vol. 12, no. 2, pp. 1185-1193. doi: https://doi.org/10.1109/TSG.2020.3027371.

11. Hingoranl N.G., Gyugyi L., El-Hawary M.E. *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. Wiley-IEEE Press, 1999. 432 p. doi: https://doi.org/10.1109/9780470546802.

12. Hingorani N.G. FACTS-flexible AC transmission system. *International Conference on AC and DC Power Transmission*, London, UK, 1991, pp. 1-7.

13. Hingorani N.G. *Flexible AC transmission system (FACTS). Electricity Transmission Pricing and Technology*. Springer, Dordrecht, 1996.

14. Singh A.R., Ahmed A., Dambhare S. Robust distance protection of mid-point shunt compensated transmission line. *2012 IEEE Fifth Power India Conference*, 2012, pp. 1-5. doi: https://doi.org/10.1109/PowerI.2012.6479485.

15. Chemidi A., Benhabib M.C., Bourouis M.A. Performance improvement of shunt active power filter based on indirect control with a new robust phase-locked loop. *Electrical Engineering & Electromechanics*, 2022, no. 4, pp. 51-56. doi: https://doi.org/10.20998/2074-272X.2022.4.07.

16. Sekhane H., Labed D., Labed M.A. Modelling and performance testing of a digital over-current relay enhanced designed model. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 71-78. doi: https://doi.org/10.20998/2074-272X.2022.3.10.

Received 31.08.2022
Accepted 19.12.2022
Published 07.03.2023

A. Jani[1], *PhD*, *Research Scholar*,
V.H. Makwana[2], *PhD*, *Professor*,
[1] Gujarat Technological University, India,
e-mail: Asg.8491@gmail.com (Corresponding Author)
[2] GH Patel College of Engineering and Technology, India,
e-mail: Vijay911979@gmail.com

How to cite this article:
Jani A., Makwana V.H. Modified discrete Fourier transform algorithm for protection of shunt compensated distribution line. *Electrical Engineering & Electromechanics*, 2023, no. 2, pp. 63-68. doi: https://doi.org/10.20998/2074-272X.2023.2.10