

RESEARCH ARTICLE

Microgrid Protection Enhancement Using Voltage Restrained Overcurrent Relay: Case Study of Semaui Island

Abdulloh Iskandar¹, Margo Pujiantara*, Ardyono Priyadi

¹ Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

*Corresponding author (margo@ee.its.ac.id).

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Abstract

The adoption of renewable energy sources in microgrids has increased rapidly in recent years; some microgrids operate in a hybrid operation, fully supplied by photovoltaic (PV) during the day and using diesel engine generator (DEG) at night. The increase in inverter-based renewable energy sources has an impact on the character of the grid when a short circuit fault occurs. In synchronous generator-based power plants, the contribution of the short circuit current generated is very large. Meanwhile, in inverter-based power plants, the short circuit current generated is not much different from the nominal current. In these conditions, conventional overcurrent protection relays (OCR) are no longer effective in protecting the grid, so development is needed so that the grid remains safe and the fault can be isolated properly and quickly. The proposed relay is a voltage restrained overcurrent relay (VR-OCR). This relay is expected to be able to detect faults and isolate them quickly both in synchronous generator-based and inverter-based sources. Proof of the effectiveness of using VR-OCR was carried out by simulation using ETAP software. The results of this study indicate that when generating only from PV, the overcurrent relay does not operate when a short circuit fault occurs. After VR-OCR is activated, all relays through which the short circuit current passes can operate with the last relay operating at 1723 ms

Keywords: microgrid, protection relay, short circuit, voltage restrained overcurrent

I. INTRODUCTION

We are now entering the era of renewable energy sources (RES), and it is estimated that in the future the portion of RES connected to the grid will increase, and RES may even dominate the power plant energy mix. The Indonesian government is targeting that by 2030; the RES mix will reach 34% of the total power generation [1]. Some RES generators are inverter-based. If many steam turbines, gas turbines, or hydro power plants are used, synchronous generators can produce quite large short-circuits, while inverter-based RES generators cannot produce large short-circuits. Too large a short-circuit value can have a negative impact on the equipment, which can cause serious damage to the equipment when a fault occurs. However, if the short-circuit is too low, it will be difficult to determine the overcurrent protection setting, because the fault current value is almost equivalent to the normal current value of the equipment, so that traditional overcurrent-based protection relays cannot detect faults accurately and the overcurrent relay may not work when a short-circuit fault occurs [2]. If the fault in the distribution network is not isolated as soon as possible, it could lead to a major effect of unstable operation that may lead to eventual blackout and cause greater losses [3].

In literature [4], a new protection method for inverter-based microgrids using only current polarity comparison has been carried out. This method uses the phase difference between the current components before the fault and the fault current to detect the direction of the fault. With the proposed method, the faulty internal parts can be identified in

autonomous microgrids. The inverter-based microgrid model is simulated using PSCAD/EMTDC software and the signal is processed using MATLAB. The results show that the proposed method can detect faults in inverter-based microgrids. However, this method is only for the protection of a specific area where the current direction is unidirectional and is less effective for systems with changeable current directions.

A system protection strategy for inverter based microgrid (IBMG) on an island containing a voltage-frequency-controlled inverter-based distributed energy resource (VF-IBDER) is proposed as the source of IBMG [5]. This strategy includes VF-IBDER short-circuit fault modeling, fault detection method, and protection coordination strategy. First, the control structure of VF-IBDER under short-circuit conditions is presented. Then, a sequence component network is generated to determine the behavior of VF-IBDER under short-circuit condition. Furthermore, using the sequence network, a voltage-limited negative sequence resistance-based fault detection method is proposed. This fault detection method does not rely on the large magnitude of the fault current and does not require communication infrastructure. Since this method uses negative sequence current parameters, it is less effective for symmetrical faults.

In article [6], a protection coordination strategy for networked microgrids (NMG) is proposed using nonstandard tripping characteristic (NSTC) on directional overcurrent relay (DOCR). The concept of relay setting group (RSG) is embedded in the proposed protection scheme to consider

various network topologies including multiple network-connected events and unique relay settings are designed for each RSG. Variation of operating conditions by varying distributed generator (DG) power penetration and DG outages are also examined and validated. The proposed relay tripping characteristic can be easily embedded in modern numerical relays for field applications. The proposed protection scheme requires assistance of reliable communication infrastructure so that the settings are in accordance with the actual system conditions.

In paper [7], a study has been conducted on the fault diagnostic scheme using Recurrent Graph Neural Network (RGNN) which can detect faults, classify fault types, find fault phases and identify fault locations. This method produces better accuracy compared to machine learning techniques and other NN structures such as ANN, RNN, CNN and GCN. The level of difficulty in implementing RGNN in the field. For radial systems with close distances between feeders, it will be difficult to distinguish which feeder is experiencing a disturbance if only using voltage parameters. It does not include systems with hybrid generators.

Literature [8] proposes a grid-forming inverter that can provide high current during power outages. With minor changes, it can produce short-circuit currents over three times the nominal current. This will enhance fault current magnitude, enabling reliable use of affordable protection in microgrids. Although the current generated is higher, it still does not match the short-circuit current from synchronous generators.

A good protection system is crucial for ensuring the reliability and stability of electric power systems. In microgrid systems that use renewable energy, a hybrid approach combines solar cells during the day with diesel power at night. The current protection system can function during disturbances from the diesel generator but may fail during issues with solar energy. If this problem isn't fixed, it could slow down the use of renewable energy power plants. Properly isolating disturbances is expected to enhance the reliability of the electricity distribution system for broader adoption of renewable energy sources.

This paper studied voltage restraint overcurrent protection relays (VR-OCR) for hybrid microgrid systems that use solar cells during the day and diesel engine generator at night. The system is simulated with ETAP software. The study aims to find a suitable protection method for hybrid microgrids, focusing on the Semaui island microgrid case. The key contributions of this paper are described as follows:

- Enhance microgrid protection so that the network is protected from short circuit disturbances when using synchronous generators (SG) or inverter-based renewable energy generators (IBR).
- Find the type of protection that can be used to protect the hybrid microgrid system from short circuits.
- Simulating the effectiveness of VR-OCR in protecting microgrids from short circuit faults.

II. VOLTAGE RESTRAINED OVERCURRENT RELAY

A. Short Circuit Characteristics in Microgrid Distribution Systems

In the microgrid distribution system network, distributed generation can be synchronous generators or inverter-based renewable energy generators. The main difference between synchronous generators and IBRs is the source characteristics and dynamic conditions of their control systems.

The contribution current from synchronous generators (i_{SG}) can be represented by the equation (1).

$$i_{SG} = \sqrt{i_{ac}^2 + i_{dc}^2} \quad (1)$$

Where i_{ac} is the AC component current and i_{dc} is the DC component current. In general, the short circuit current generated by a synchronous generator can be much larger than the nominal current of the generator.

TABLE I. COMPARISON OF SG BASED AND IBR BASED GENERATION

Parameter	SG based	IBR based
Short circuit current	high	low
Inertia	Have enough inertia	Have no inertia
Predictability	More predictable	More dynamic

In inverter-based resources, the resulting short-circuit contribution current is not much different from the nominal inverter current so that the use of conventional overcurrent protection relays is no longer effective. Comparison of SG and IBR characteristics can be seen in Table I.

B. Voltage Restrained Overcurrent Protection Relay

Voltage restrained overcurrent protection relay is an advanced type of overcurrent protection relay. It serves as backup protection for generators and systems, preventing damage during disturbances that main protection cannot handle. During a short circuit, the fault current from the generator may be lower than the full load current due to the synchronous reactance of the machine. If the generator's excitation power comes from its terminal, the voltage drop during a short circuit can further reduce fault current, making normal overcurrent protection ineffective. The AVR can sometimes help maintain a higher fault current, but if it fails, voltage restrained overcurrent protection is necessary as backup [9]. The voltage restrained overcurrent operation curve can be seen in Figure 1.

The application of time-current curve (TCC) changes on VR-OCR can be seen in Figure 2. When the voltage is over 90% of the rated voltage, the relay operates like curve A. However, when the voltage drops to 75% of the rated voltage, the relay's operation curve changes to curve B, which operates at 75% of curve A. If the voltage falls to 50% of the rated voltage, the relay shifts to curve C. This continues until the voltage drops below 10% of the rated voltage, where the relay operates at 10% of curve A. This working principle of VR-OCR can help protect against short-circuit faults in a microgrid supplied only by inverter-based generation, ensuring the microgrid remains protected from such faults.

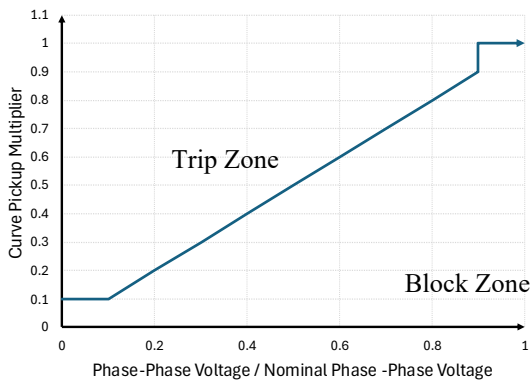


Fig. 1. Tripping characteristic of VR-OCR

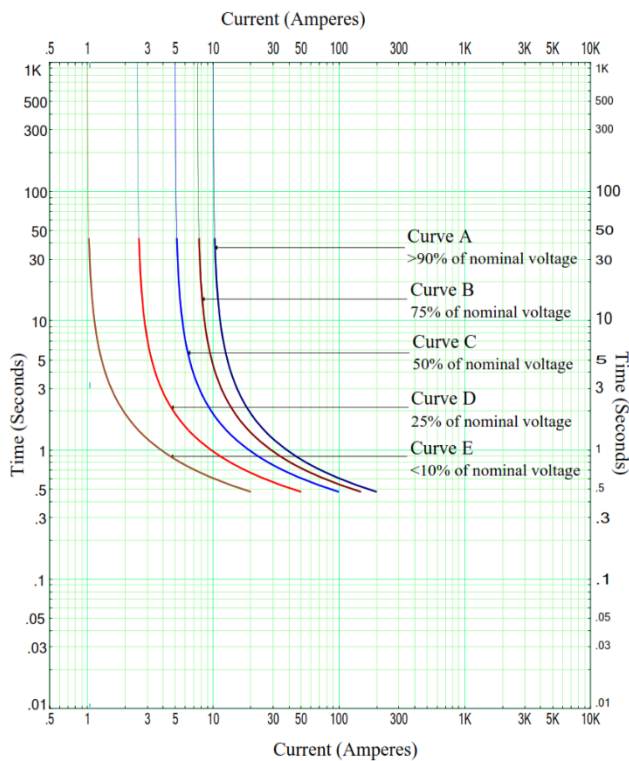


Fig. 2. Operating curve of VR-OCR at several voltage conditions

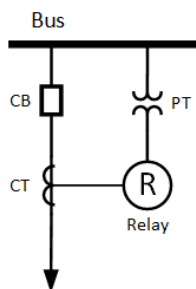


Fig. 3. VR-OCR connection scheme

The VR-OCR connection scheme also has differences from the overcurrent relay. In the overcurrent relay, it only uses current sensing. However, in the VR-OCR, current and voltage sensing are used. So, in addition to using a current transformer, VR-OCR also requires sensing from a potential

transformer (PT). The VR-OCR connection scheme can be seen in Figure 3.

III. CASE STUDY IN SEMAU ISLAND MICROGRID

Semau Island is in the province of East Nusa Tenggara with a stand-alone electricity network. The total power generation capacity on Semau Island is 1460 kW with a peak load of 450 kW. The types of power plants on Semau Island consist of 5 diesel power plants and solar power plants. The installed power of the PLTS is 450 kWp, the inverter capacity is 400 kW and the battery capacity is 2.9 MWh. With this capacity, solar power can meet the electricity supply needs during the day. At night the power plant will be supplied by diesel. The single line diagram of the Semau Island microgrid can be seen in Figure 4. On the semau island network there are five diesel power plants. the capacity of each machine can be seen in table II.

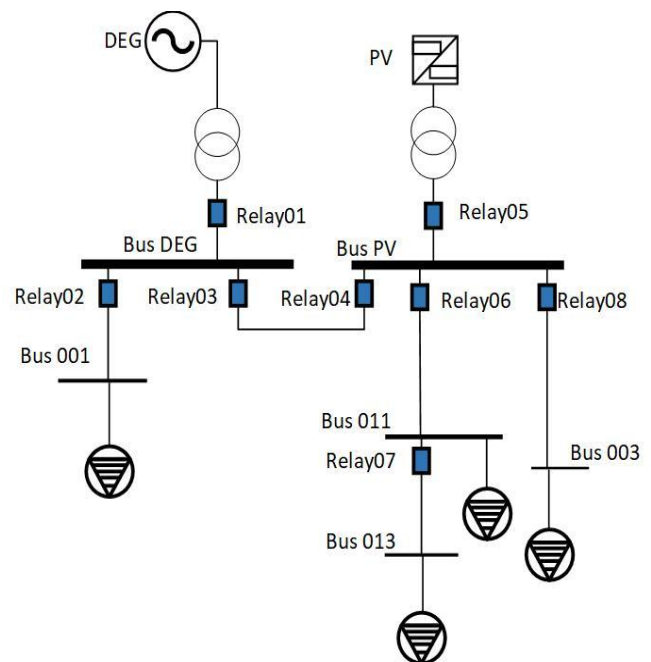


Fig. 4. Single line diagram of Semau island microgrid

TABLE II. GENERATION CAPACITY OF SEMAU ISLAND MICROGRID

Number	Engine	Net Capacity	Voltage
G1	Deutz	100 kW	380 V
G2	MTU-MDEC	280 kW	380 V
G3	MTU-ADEC	280 kW	380 V
G4	Volvo	140 kW	380 V
G5	MWM	70 kW	380 V

The system is simulated with ETAP software. Based on the operating pattern of Semau Island microgrid in Figure 5, the generation pattern can be categorized into five cases which can be seen in table III. This generation scenario is used to represent the conditions when the system uses SG or IBR. so that the research results can be applied in every possible condition of the operating pattern in the Semau Island microgrid. Case A has similar characteristics to case E. Case B has similar characteristics to case C. So, in this paper, simulations are present for cases A, C and D only.

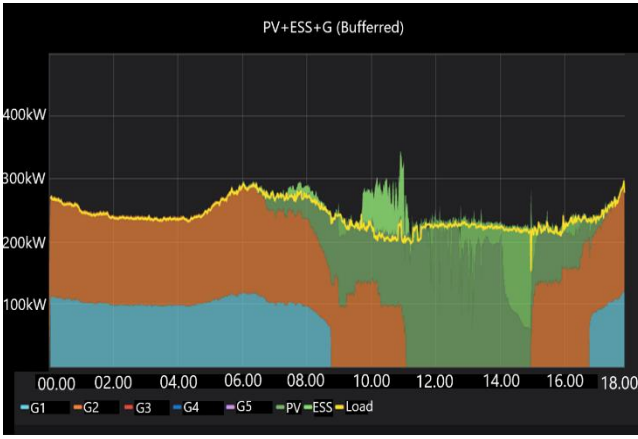


Fig. 5. Operation mode Semau Island microgrid

TABLE III. GENERATION SCENARIO

Case	G1	G2	G4	PV+ESS
A	ON	ON	OFF	OFF
B	ON	ON	OFF	ON
C	OFF	ON	OFF	ON
D	OFF	OFF	OFF	ON
E	ON	ON	ON	OFF

IV. RESULTS AND DISCUSSION

A. Short Circuit Current Value

In this study, simulation of the minimum and maximum short-circuit currents was performed on each main bus. The minimum short-circuit current obtained in 30 cycles was used to calculate the instantaneous relay current setting. While the maximum short-circuit current was used as the reference current in the time dial calculation. These values can be seen in Table IV. Meanwhile, the current and voltage values sensed by the protection relay are shown in Table V.

B. Protection Relay Setting Calculation

The inverse time overcurrent relay (51) is used to protect equipment from overloads, so it is set based on the rated current of the protected equipment. The current setting (I_s) of the inverse time overcurrent relay is 105% to 140% of the equipment's rated current. The type of curve selected is IEEE moderately inverse. The time dial (TD) setting is calculated based on the equation (2) where t is the desired operating time when reaching the current (I).

$$TD = \frac{t}{\left(\frac{0.0515}{\left(\frac{I}{I_s} \right)^{0.02} - 1} + 0.1140 \right)} \quad (2)$$

The instantaneous overcurrent relay (50) is used to protect equipment from short-circuit faults, so instantaneous current pickup ($I_{>>}$) is set based on the short-circuit current sensed by the relay. The relay instantaneous overcurrent relay setting must be less than 80% of the minimum short-circuit current. The time delay setting is selected based on the relay's operating sequence. According to IEEE 242-2001, the recommended current time interval (CTI) is 0.20 s to 0.30 s [10].

To simplify the calculation of protection coordination settings in the Semau Island microgrid, the electrical system is simplified and a typical path is taken which is the longest

path from the generator to the load. This typical path can represent the Semau Island microgrid electrical system and will be a reference in setting protection coordination at other points. The typical path is shown with red line in Figure 6. From this typical path, the protection relays passed are relay07, relay06, relay05, relay04, relay03 and relay01. There is no branching between relay04 and relay03, so the relay settings can be the same. Therefore, only one relay is calculated. A summary of the OCR settings can be seen in Table VI.

TABLE IV. MINIMUM AND MAXIMUM FAULT CURRENT ON BUS

Bus	Minimum SC current	Maximum SC current
Bus DEG	0.043 kA	0.096 kA
Bus PV	0.043 kA	0.096 kA
Bus 011	0.043 kA	0.096 kA

TABLE V. FAULT CURRENT AND VOLTAGE ON BUS 013

Case	Current	Voltage
A	0.043 kA	0.343%
B	0.053 kA	0.425%
C	0.043 kA	0.339%
D	0.017 kA	0.138%
E	0.057 kA	0.458%

TABLE VI. RELAY PROTECTION SETTING FOR OCR

Relay name	I_s	TD	$I_{>>}$	t
Relay07	0.26	0.05	0.34	0.1 s
Relay06	0.30	0.14	0.34	0.3 s
Relay04	0.33	0.21	0.34	0.5 s
Relay01	0.335	0.30	0.34	0.7 s
Relay05	0.27	0.46	0.34	0.9 s

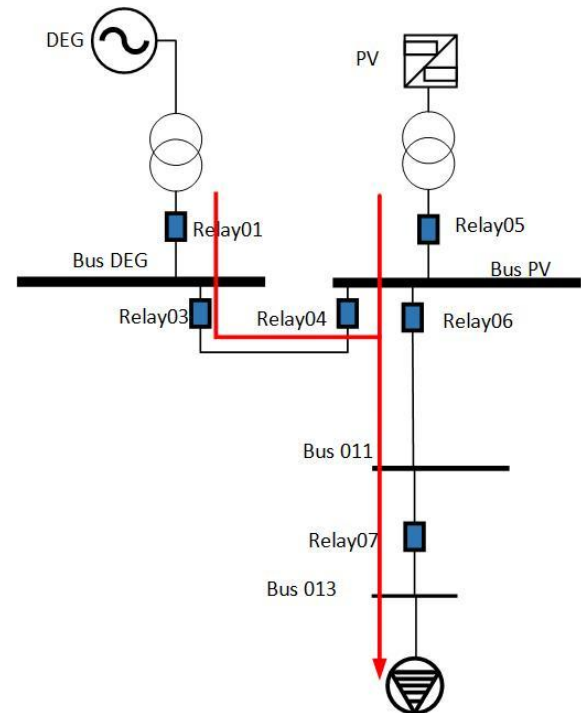


Fig. 6. Typical path of protection relay coordination

In the VR-OCR setting, there is a difference in the time dial setting because the curve can shift according to the voltage conditions read by the relay. The pickup current entered into the time dial calculation equation is 10% of the pickup current setting so that when the short circuit current is maximum, the VR-OCR relay continues to operate after the instantaneous relay. If the calculation directly uses the pickup current as in the OCR calculation, then when a high voltage drop occurs, the VR-OCR can operate before the instantaneous relay. The results of the setting calculations for VR-OCR can be seen in Table VII.

TABLE VII. RELAY PROTECTION SETTING FOR VR-OCR

Relay name	$I_{>}$	TD	$I_{>>}$	t
Relay07	0.26	0.13	0.34	0.1 s
Relay06	0.30	0.38	0.34	0.3 s
Relay04	0.33	0.61	0.34	0.5 s
Relay01	0.335	0.86	0.34	0.7 s
Relay05	0.27	1.17	0.34	0.9 s

C. Simulation for case A

First, the system is simulated using an overcurrent relay with the generation of case A, with the generation source G1 and G2, the flow of which is shown in Figure 7. The fault current (I_f) is 43 A, so the relay can operate to protect the system. The simulation results are as shown in table VIII and Figure 8. Table VIII shows the trip sequence in case A simulation using overcurrent protection relay. Figure 8 shows the TCC of the operating relay. From the simulation, the overcurrent relay can operate properly when a disturbance occurs in case A.

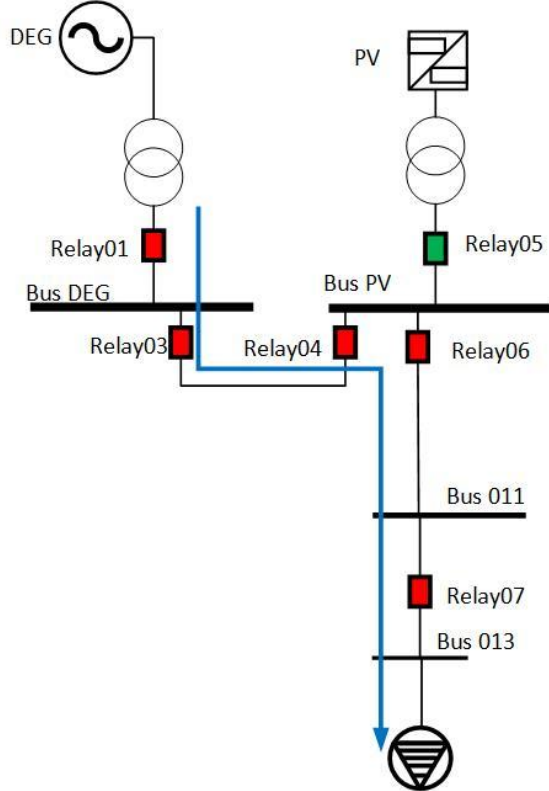


Fig. 7. Tipikal path for case A

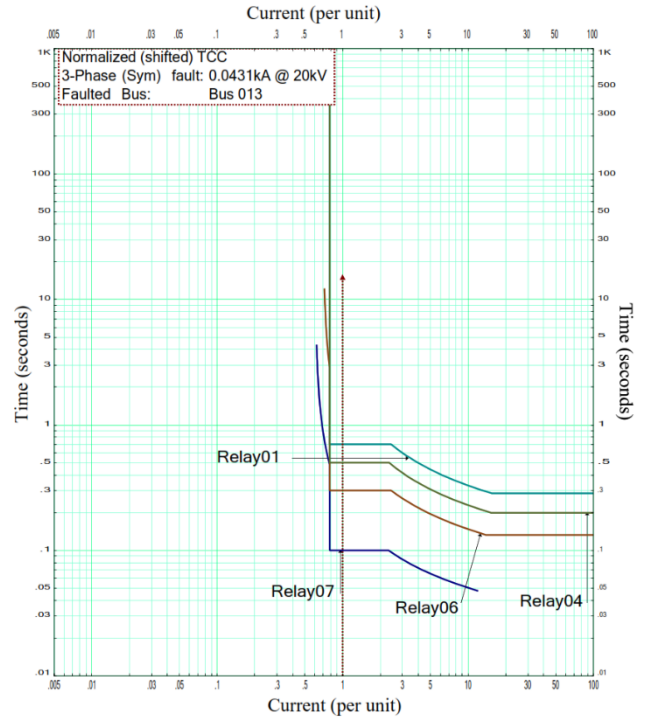


Fig. 8. TCC OCR for case A

TABLE VIII. SEQUENCE OF OPERATION FOR OCR CASE A

Time (ms)	Relay name	I_f (kA)	Condition
100	Relay07	0.043	Phase-OC1-50
259	Relay07	0.043	Phase-OC1-51
300	Relay06	0.043	Phase-OC1-50
500	Relay04	0.043	Phase-OC1-50
700	Relay01	0.043	Phase-OC1-50
1006	Relay06	0.043	Phase-OC1-51
2040	Relay04	0.043	Phase-OC1-51
3086	Relay01	0.043	Phase-OC1-51

All relays 50 through which the contributing current passes have operated, even though only an overcurrent relay is used. Therefore, even if VR-OCR is activated, it does not change the order of the active protection relays. However, there is a difference in the operating time of relay 51, but it is still preceded by relay 50. The operating sequence of the protection relays can be seen in Table IX and Figure 9.

Due to different setting calculations, the settings on the conventional overcurrent relay must be changed when the VR-OCR is activated. The time dial setting on the VR-OCR will be higher than the time dial setting on the conventional overcurrent relay. In condition A where the supply is only from the PLTD, if the instantaneous overcurrent protection relay (50) is activated, there is no difference between the use of OCR and VR-OCR because the one that operates is relay 50 which has a fixed operating time. However, when relay 50 is deactivated or when relay 50 fails to operate, there is a difference in operating time. VR-OCR operates faster than OCR. This has a positive impact that VR-OCR will isolate the fault more quickly and can be a better backup for relay 50.

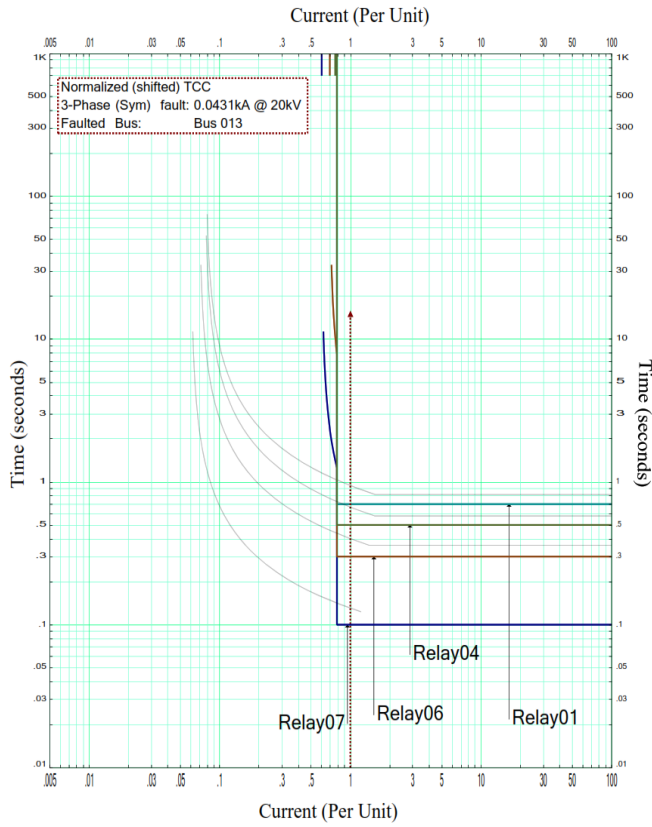


Fig. 9. TCC VR-OCR for case A

TABLE IX. SEQUENCE OF OPERATION FOR VR-OCR CASE A

Time (ms)	ID	If (kA)	Condition
100	Relay07	0.043	Phase-OC1-50
131	Relay07	0.043	Phase-OC1-51-Vrest (10%)
300	Relay06	0.043	Phase-OC1-50
401	Relay06	0.043	Phase-OC1-51-Vrest (10%)
500	Relay04	0.043	Phase-OC1-50
665	Relay04	0.043	Phase-OC1-51-Vrest (10%)
700	Relay01	0.043	Phase-OC1-50
943	Relay01	0.043	Phase-OC1-51-Vrest (10%)

D. Simulation for case C

In case C, as seen in Figure 10, the PV has supplied more power so that the G1 diesel generator can be turned off, leaving only one diesel engine generator, G2. The current contribution from G2 is not enough to trip the relay, so only relays 06 and 07 can operate. The sequence of operation of the protection relays can be seen in Table X and Figure 11.

There are many changes after activating VR-OCR. Relays that do not operate when using OCR when a short circuit occurs now operate with a fast operating time and can protect the system from short circuit disturbances. These relays include: relay04, relay03, relay01 and relay05. The sequence of relay operations for condition C can be seen in table XI and figure 12.

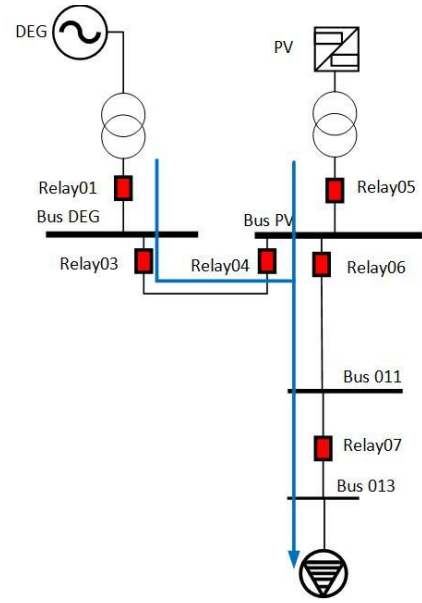


Fig. 10. Tipikal path for case C

TABLE X. SEQUENCE OF OPERATION FOR OCR CASE C

Time (ms)	Relay name	If (kA)	Condition
100	Relay07	0.043	Phase-OC1-50
264	Relay07	0.043	Phase-OC1-51
300	Relay06	0.043	Phase-OC1-50
1034	Relay06	0.043	Phase-OC1-51

TABLE XI. SEQUENCE OF OPERATION FOR VR-OCR CASE C

Time (ms)	ID	If (kA)	Condition
100	Relay07	0.043	Phase-OC1-50
131	Relay07	0.043	Phase-OC1-51-Vrest (10%)
300	Relay06	0.043	Phase-OC1-50
402	Relay06	0.043	Phase-OC1-51-Vrest (10%)
748	Relay04	0.032	Phase-OC1-51-Vrest (10%)
1061	Relay01	0.032	Phase-OC1-51-Vrest (10%)
1721	Relay05	0.017	Phase-OC1-51-Vrest (10%)

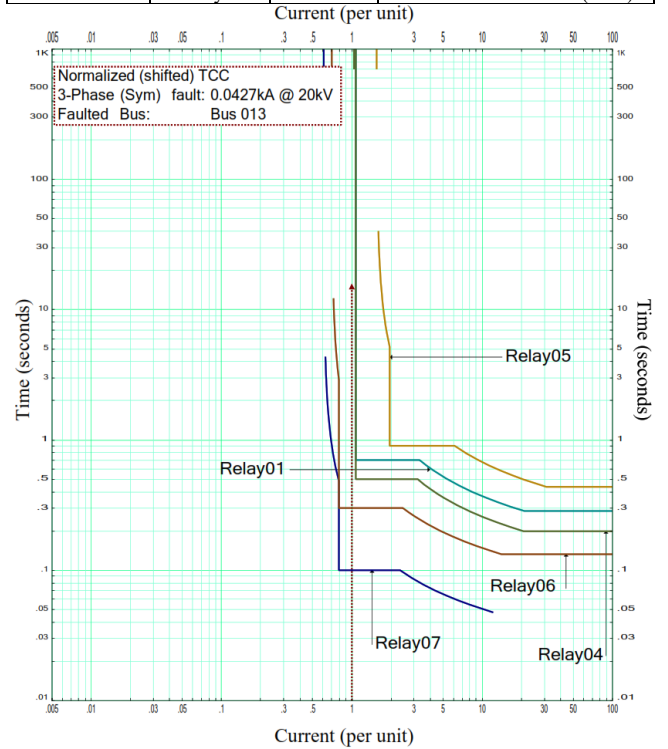


Fig. 11. TCC OCR for case C

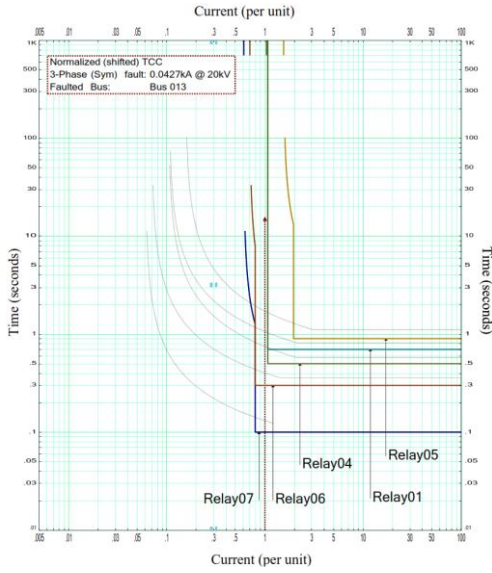


Fig. 12. TCC VR-OCR for case C

E. Simulation for case D

In case D, as seen in Figure 13, the PV has taken over the entire power supply, the short-circuit current is quite small, and the overcurrent protection relay cannot sense the fault, so no devices trip, as shown in Table XII and Figure 14. Case D is a condition that has significant changes after activating VR-OCR. While no relays operate during OCR, when VR-OCR is used, all relays through which the fault current passes will trip successfully. The relay operation sequence for condition D can be seen in Table XIII and Figure 15.

TABLE XII. SEQUENCE OF OPERATION FOR OCR CASE D

Time (ms)	ID	If (kA)	Condition
-	-	-	No device tripped

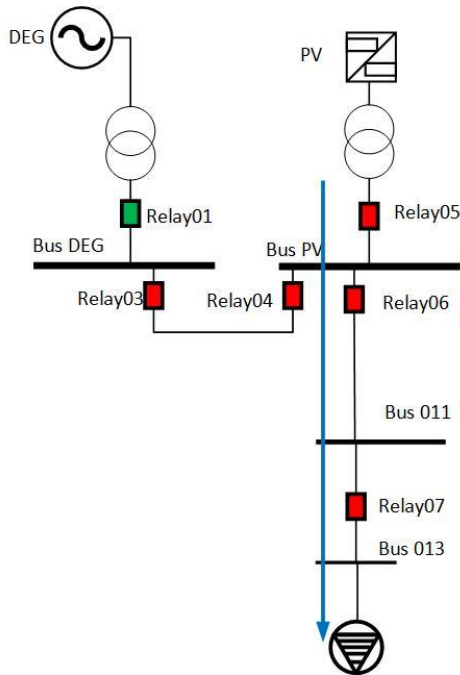


Fig. 13. Tipikal path for case D

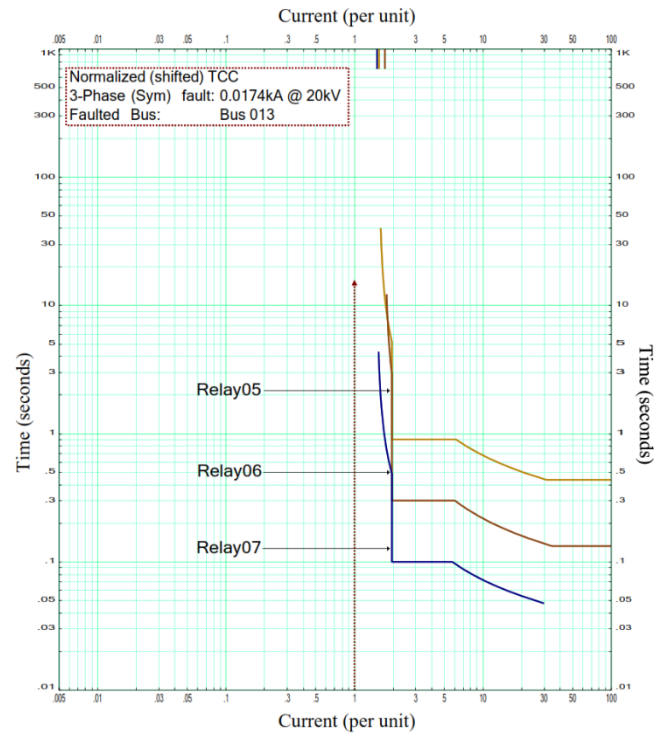


Fig. 14. TCC OCR for case D

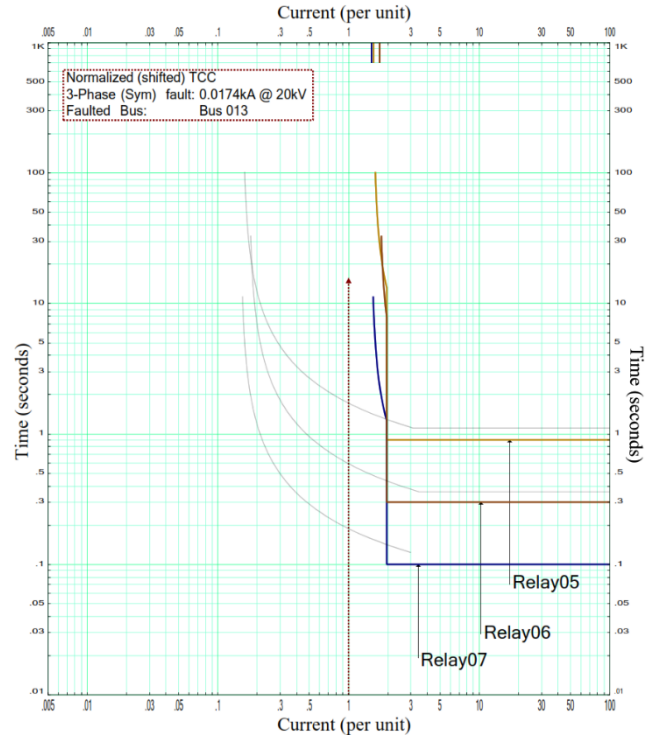


Fig. 15. TCC VR-OCR for case D

TABLE XIII. SEQUENCE OF OPERATION FOR OCR CASE D

Time (ms)	ID	If (kA)	Condition
188	Relay07	0.017	Phase-OC1-51-Vrest (10%)
591	Relay06	0.017	Phase-OC1-51-Vrest (10%)
1723	Relay05	0.017	Phase-OC1-51-Vrest (10%)

From the simulation results, it is found that when a short circuit occurs with the network supply from the diesel power plant, the conventional overcurrent protection relay can

operate normally, but when the network supply comes from the PV, the overcurrent relay does not operate when a short circuit occurs. After activating VR-OCR, protection relays can operate properly and coordinated.

V. CONCLUSION

Research shows that voltage restrained overcurrent relay can improve the protection system of hybrid microgrids that use solar power during the day and diesel engine generator at night. In conditions where the network is only supplied by solar power plants, the short-circuit current generated is not enough to make the overcurrent relay work. After the voltage restrained overcurrent relay is activated, all relays through which the short-circuit current passes can operate with the last relay operating at 1676 ms. In condition A which does not use PV generators, VR-OCR can be useful in shortening the total operation time of relay 51 from 8431 ms to 2805 ms, as a backup of instantaneous overcurrent relay when a short circuit occurs.

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